IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

GUARDIAN INDUSTRIES CORP.,	)	
Plaintiff,	)	**CA No.:**
v.	)	
	)	**Jury Trial Demanded**
INNOLUX DISPLAY CORP.,	)	
Defendant.	)	

COMPLAINT FOR PATENT INFRINGEMENT

Plaintiff Guardian Industries Corp. ("Guardian") for its complaint against defendant InnoLux Display Corp. ("InnoLux") alleges as follows:

NATURE OF THE ACTION

1. This is an action under the patent laws of the United States, 35 U.S.C. §§ 1, *et seq.*, for infringement by InnoLux of patents owned by Guardian.

2. The technology at issue involves the design and manufacture of liquid crystal displays ("LCDs") and related products (collectively "LCD Products"). An LCD is a type of flat panel display that is used in products such as computer monitors.

3. Guardian is the owner of United States Patent No. 5,570,214 (the "'214 Patent") entitled "Normally White Twisted Nematic LCD with Retardation Films on Opposite Sides of Liquid Crystal Material for Improved Viewing Zone."

4. Guardian is the owner of United States Patent No. 5,694,187 (the "'187 Patent") entitled "LCD Including A Negative Biaxial Retarder On Each Side Of The Liquid Crystal Layer."

5. Guardian is the owner of United States Patent No. 6,226,065 (the "'065 Patent") entitled "Liquid Crystal Display Having High Contrast Viewing Zone Centered in Positive or Negative Vertical Region."

6. Guardian is the owner of United States Patent No. 6,229,588 (the "'588 Patent") entitled "Normally White LCD Including First and Second Biaxial Retarders."

7. This is a civil action for the infringement of the '214 Patent, the '187 Patent, the '065 Patent, and the '588 Patent (collectively, the "Patents-in-Suit") by InnoLux. Guardian owns the Patents-in-Suit and possesses the right to sue and to recover for infringement of the Patents-in-Suit. Copies of the Patents-In-Suit are attached hereto.

8. Guardian and/or predecessor owners of the Patents-In-Suit marked their products under 35 U.S.C. § 287(a).

THE PARTIES

9. Plaintiff Guardian is a corporation organized under the laws of the state of Delaware with its principal place of business at 2300 Harmon Road, Auburn Hills, Michigan, 48326-1714.

10. On information and belief, InnoLux is a Taiwanese corporation with its principal place of business at 160 Ke Syue Road, Hsingchu Science Park, Chu-Nan 350, Miao-Li County, Taiwan R.O.C.

11. On information and belief, InnoLux sells LCD product(s) that include a version of Fuji Wide View (WV) film.

JURISDICTION AND VENUE

12. Subject matter jurisdiction is proper in this Court under 28 U.S.C. §§ 1331 and 1338(a).

13. This Court has personal jurisdiction over the InnoLux because InnoLux has purposely availed itself of the privilege of conducting activities within this State and District, and/or have conducted activities elsewhere in the United States.

14. Venue is proper in this Judicial District under 28 U.S.C. §§ 1391(b-c) and 1400(b).

COUNT I - INFRINGEMENT OF THE '214 PATENT

15. Guardian realleges and incorporates herein by reference the allegations stated in paragraphs 1-14 of this Complaint.

16. The '214 patent was duly and legally issued on October 29, 1996. The '214 Patent was duly and legally assigned to Guardian, and Guardian owns and has full rights to sue, enforce and recover damages for all infringements of the '214 patent. Pursuant to Local Rule 3.2, a true and correct copy of the '214 Patent is attached to this Complaint as Exhibit 1.

17. InnoLux has infringed, contributorily infringed and/or actively induced infringement, and on information and belief is infringing, contributorily infringing and/or actively inducing infringement of the '214 patent in this District, in the United States and elsewhere by at least making, importing, causing to be imported, using, causing to be used, offering to sell, causing to be offered for sale, selling and/or causing to be sold LCDs and/or products relating to LCDs that infringe one or more claims of the '214 Patent.

18. On information and belief, InnoLux will continue to infringe, contributorily infringe and/or actively induce others to infringe the '214 Patent unless and until it is enjoined by this Court.

19. On information and belief, InnoLux has been aware of the '214 Patent since at least as early as August 2005.

20. On information and belief, InnoLux's infringement, with knowledge of the '214 Patent, has been and continues to be willful and deliberate, making this an exceptional case and entitling Guardian to increased damages and reasonable attorneys' fees, pursuant to 35 U.S.C. §§ 284 and 285.

COUNT II - INFRINGEMENT OF THE '187 PATENT

21. Guardian realleges and incorporates herein by reference the allegations stated in paragraphs 1-14 of this Complaint.

22. The '187 patent was duly and legally issued on December 2, 1997. The '187 Patent was duly and legally assigned to Guardian, and Guardian owns and has full rights to sue, enforce and recover damages for all infringements of the '187 patent. Pursuant to Local Rule 3.2, a true and correct copy of the '187 Patent is attached to this Complaint as Exhibit 2.

23. InnoLux has infringed, contributorily infringed and/or actively induced infringement, and on information and belief is infringing, contributorily infringing and/or actively inducing infringement of the '187 patent in this District, in the United States and elsewhere by at least making, importing, causing to be imported, using, causing to be used, offering to sell, causing to be offered for sale, selling and/or causing to be sold LCDs and/or products relating to LCDs that infringe one or more claims of the '187 Patent.

24. On information and belief, InnoLux will continue to infringe, contributorily infringe and/or actively induce others to infringe the '187 Patent unless and until it is enjoined by this Court.

25. On information and belief, InnoLux has been aware of the '187 Patent since at least as early as August 2005.

26. On information and belief, InnoLux's infringement, with knowledge of the '187 Patent, has been and continues to be willful and deliberate, making this an exceptional case and

entitling Guardian to increased damages and reasonable attorneys' fees, pursuant to 35 U.S.C. §§ 284 and 285.

COUNT III- INFRINGEMENT OF THE '065 PATENT

27. Guardian realleges and incorporates herein by reference the allegations stated in paragraphs 1-14 of this Complaint.

28. The '065 patent was duly and legally issued on May 1, 2001. The '065 Patent was duly and legally assigned to Guardian, and Guardian owns and has full rights to sue, enforce and recover damages for all infringements of the '065 patent. Pursuant to Local Rule 3.2, a true and correct copy of the '065 Patent is attached to this Complaint as Exhibit 3.

29. InnoLux has infringed, contributorily infringed and/or actively induced infringement, and on information and belief is infringing, contributorily infringing and/or actively inducing infringement of the '065 patent in this District, in the United States and elsewhere by at least making, importing, causing to be imported, using, causing to be used, offering to sell, causing to be offered for sale, selling and/or causing to be sold LCDs and/or products relating to LCDs that infringe one or more claims of the '065 Patent.

30. On information and belief, InnoLux will continue to infringe, contributorily infringe and/or actively induce others to infringe the '065 Patent unless and until it is enjoined by this Court.

31. On information and belief, InnoLux has been aware of the '065 Patent since at least as early as August 2005.

32. On information and belief, InnoLux's infringement, with knowledge of the '065 Patent, has been and continues to be willful and deliberate, making this an exceptional case and entitling Guardian to increased damages and reasonable attorneys' fees, pursuant to 35 U.S.C. §§ 284 and 285.

COUNT IV - INFRINGEMENT OF THE '588 PATENT

33. Guardian realleges and incorporates herein by reference the allegations stated in paragraphs 1-14 of this Complaint.

34. The '588 patent was duly and legally issued on May 8, 2001. The '588 Patent was duly and legally assigned to Guardian, and Guardian owns and has full rights to sue, enforce and recover damages for all infringements of the '588 patent. Pursuant to Local Rule 3.2, a true and correct copy of the '588 Patent is attached to this Complaint as Exhibit 4.

35. InnoLux has infringed, contributorily infringed and/or actively induced infringement, and on information and belief is infringing, contributorily infringing and/or actively inducing infringement of the '588 patent in this District, in the United States and elsewhere by at least making, importing, causing to be imported, using, causing to be used, offering to sell, causing to be offered for sale, selling and/or causing to be sold LCDs and/or products relating to LCDs that infringe one or more claims of the '588 Patent.

36. On information and belief, InnoLux will continue to infringe, contributorily infringe and/or actively induce others to infringe the '588 Patent unless and until it is enjoined by this Court.

37. On information and belief, InnoLux has been aware of the '588 Patent since at least as early as August 2005.

38. On information and belief, InnoLux's infringement, with knowledge of the '588 Patent, has been and continues to be willful and deliberate, making this an exceptional case and entitling Guardian to increased damages and reasonable attorneys' fees, pursuant to 35 U.S.C. §§ 284 and 285.

PRAYER FOR RELIEF

WHEREFORE, Plaintiff Guardian prays that this Court:

A. Enter a judgment that InnoLux has infringed, contributorily infringed and/or actively induced others to infringe the Patents-in-Suit;

B. Award Guardian damages in an amount sufficient to compensate Guardian for InnoLux's infringement, contributory infringement and/or active inducement of others' infringement of the Patents-in-Suit, but not less than a reasonable royalty;

C. Award prejudgment interest to Guardian pursuant to 35 U.S.C. § 284;

D. Award increased damages, pursuant to 35 U.S.C. § 284, in an amount not less than three times the amount of actual damages awarded to Guardian, by reason of InnoLux's willful infringement of the Patents-in-Suit;

E. Enter a permanent injunction enjoining InnoLux, its officers, directors, servants, managers, employees, agents, attorneys, successors and assignees, and all persons in active concert or participation with InnoLux, from further acts of infringement of the Patents-in-Suit, pursuant to 35 U.S.C. § 283;

F. Declare this case exceptional under 35 U.S.C. § 285 and award Guardian its reasonable attorneys' fees, expenses, and costs incurred in this action; and

G. Grant Guardian such other and further relief as this Court may deem just and proper.

JURY DEMAND

Guardian hereby demands a jury trial on all issues appropriately triable by a jury.

* * *

Dated: December 8, 2006

Richard K. Herrmann #405
MORRIS JAMES HITCHENS & WILLIAMS LLP
500 Delaware Avenue, Suite 1500
Wilmington, Delaware 19801
(302) 888-6800

Of counsel:

Bryan S. Hales
Meredith Zinanni
KIRKLAND & ELLIS LLP
200 East Randolph Drive
Chicago, Illinois 60601
(312) 861-2000

Counsel for Plaintiff Guardian Industries Corp.

US005570214A

United States Patent [19]

Abileah et al.

[11] **Patent Number: 5,570,214**

[45] **Date of Patent: Oct. 29, 1996**

[54] **NORMALLY WHITE TWISTED NEMATIC LCD WITH RETARDATION FILMS ON OPPOSITE SIDES OF LIQUID CRYSTAL MATERIAL FOR IMPROVED VIEWING ZONE**

[75] Inventors: **Adiel Abileah**, Farmington Hills; **Gang Xu**, Royal Oaks, both of Mich.

[73] Assignee: **OIS Optical Imaging Systems, Inc.**, Troy, Mich.

[21] Appl. No.: **167,652**

[22] Filed: **Dec. 15, 1993**

[51] **Int. Cl.**[6] **G02F 1/13**

[52] **U.S. Cl.** **359/73**

[58] **Field of Search** **359/73**

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,900,248	8/1975	Nagasaki	359/73
4,385,806	5/1983	Fergason	359/73
4,436,379	3/1984	Funada et al.	359/53
4,632,514	12/1986	Ogawa et al.	359/68
4,652,088	3/1987	Kando et al.	359/63
4,674,841	6/1987	Buzak	359/73
4,686,519	8/1987	Yoshida et al.	359/40
4,693,562	9/1987	Hasegawa et al.	359/63
4,701,028	10/1987	Clerc et al.	359/73
4,844,569	7/1989	Wada et al.	359/73
4,852,976	8/1989	Suzuki	359/73
4,889,412	12/1989	Clerc et al.	359/73
4,909,606	3/1990	Wada et al.	359/73
4,957,349	9/1990	Clerc et al.	359/63
4,973,137	11/1990	Kozaki	359/74
4,984,873	1/1991	Takiguchi et al.	359/63
4,984,874	1/1991	Yamamoto et al.	359/63
4,991,941	2/1991	Kalmanash	359/73
4,995,704	2/1991	Yamamoto et al.	359/73
5,018,839	5/1991	Yamamoto et al.	359/73
5,032,008	7/1991	Yamamoto et al.	359/73
5,071,997	12/1991	Harris	528/353
5,107,356	4/1992	Castleberry	359/63
5,124,824	6/1992	Kozaki et al.	359/73
5,132,826	7/1992	Johnson et al.	359/73
5,136,405	8/1992	Wada et al.	359/73
5,138,474	8/1992	Arakawa	359/73
5,150,235	9/1992	Haim et al.	359/73
5,150,237	9/1992	Iimura et al.	359/73
5,157,529	10/1992	Koopman et al.	359/73
5,179,457	1/1993	Hirataka et al.	359/73
5,184,236	2/1993	Miyashita et al.	359/73
5,189,538	2/1993	Arakawa	359/73
5,194,975	3/1993	Akatsuka et al.	359/73
5,196,953	3/1993	Yeh et al.	359/73
5,227,903	7/1993	Miyazawa et al.	359/73
5,229,039	7/1993	Ikeda et al.	359/68
5,231,521	7/1993	Johnson et al.	359/73
5,237,438	8/1993	Miyashita et al.	359/73
5,241,408	8/1993	Ishikawa et al.	359/73
5,250,214	10/1993	Kanemoto et al.	359/63
5,344,916	9/1994	Harris et al.	528/353
5,369,513	11/1994	Akatsuka et al.	359/73

FOREIGN PATENT DOCUMENTS

0349900	1/1990	European Pat. Off. .
0367616	5/1990	European Pat. Off. .
0576931	1/1994	European Pat. Off. .
55-45037	3/1980	Japan .
3-13916	1/1991	Japan .
2171549	8/1986	United Kingdom .

OTHER PUBLICATIONS

"Wide Viewing Angle LCD Using Retardation Films" by Yamagishi et al, Japan Display '89, pp. 316–319.

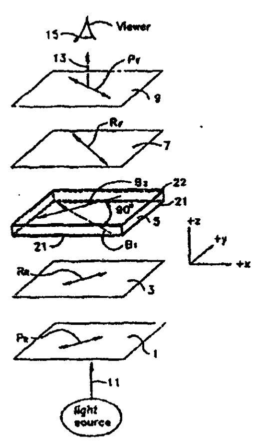
"The Symmetry Property of a 90 Degree Twisted Nematic Liquid Crystal Cell," by A. Lien.

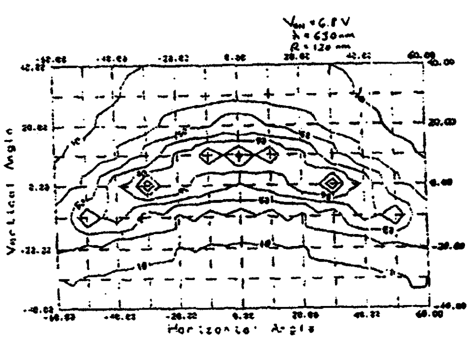
Primary Examiner—Anita Pellman Gross
Attorney, Agent, or Firm—Myers Liniak & Berenato

[57] **ABSTRACT**

A normally white twisted birefringent liquid crystal display having first and second retardation films having retardation values of about 80–200 nm on opposite sides of a liquid crystal layer for the purpose of expanding the viewing angles of the display. Also, the viewing zone of this normally white display can be shifted vertically by rotating the optical axes of the retardation films so as to position the viewing zone away from an inversion area.

48 Claims, 46 Drawing Sheets





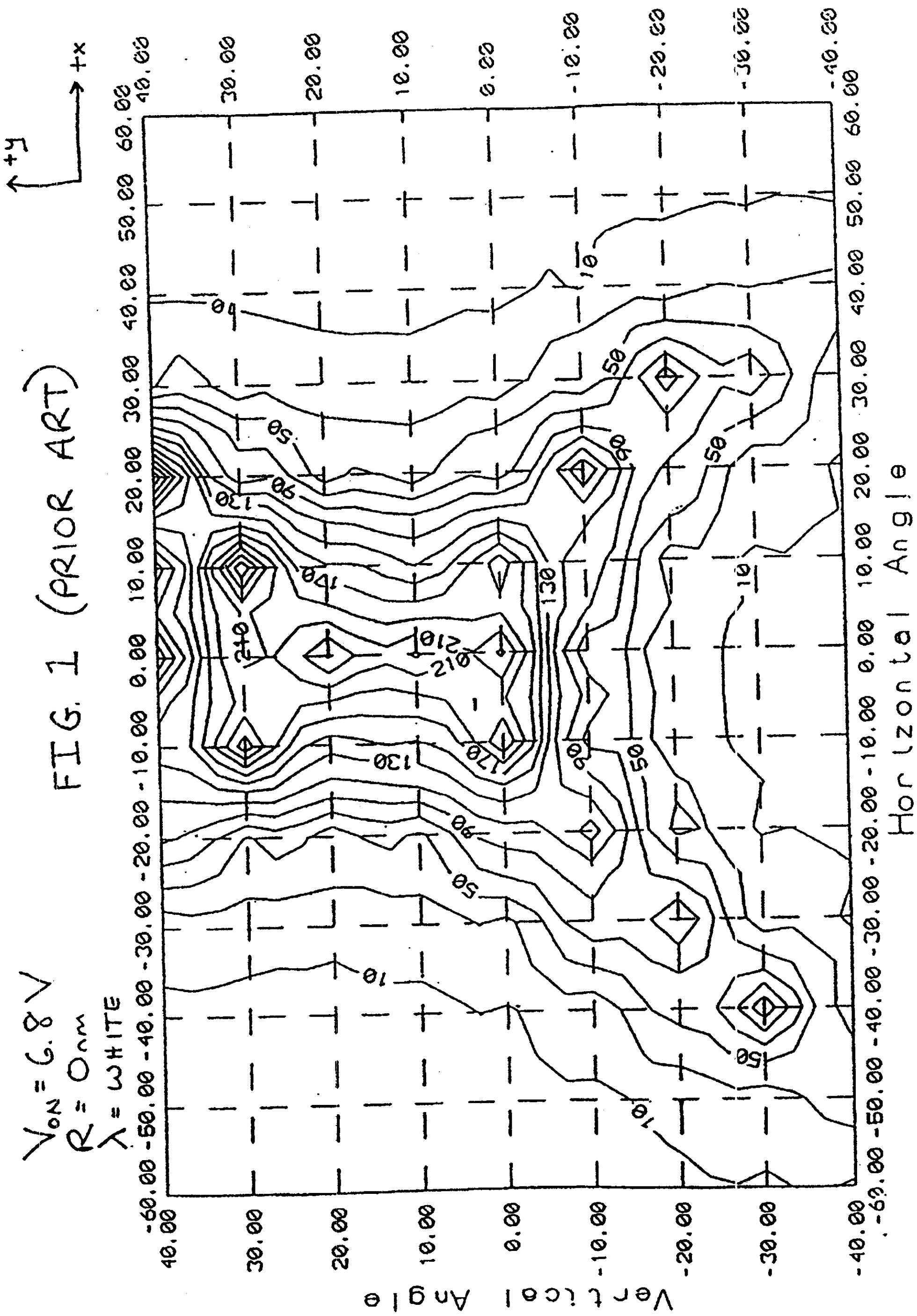
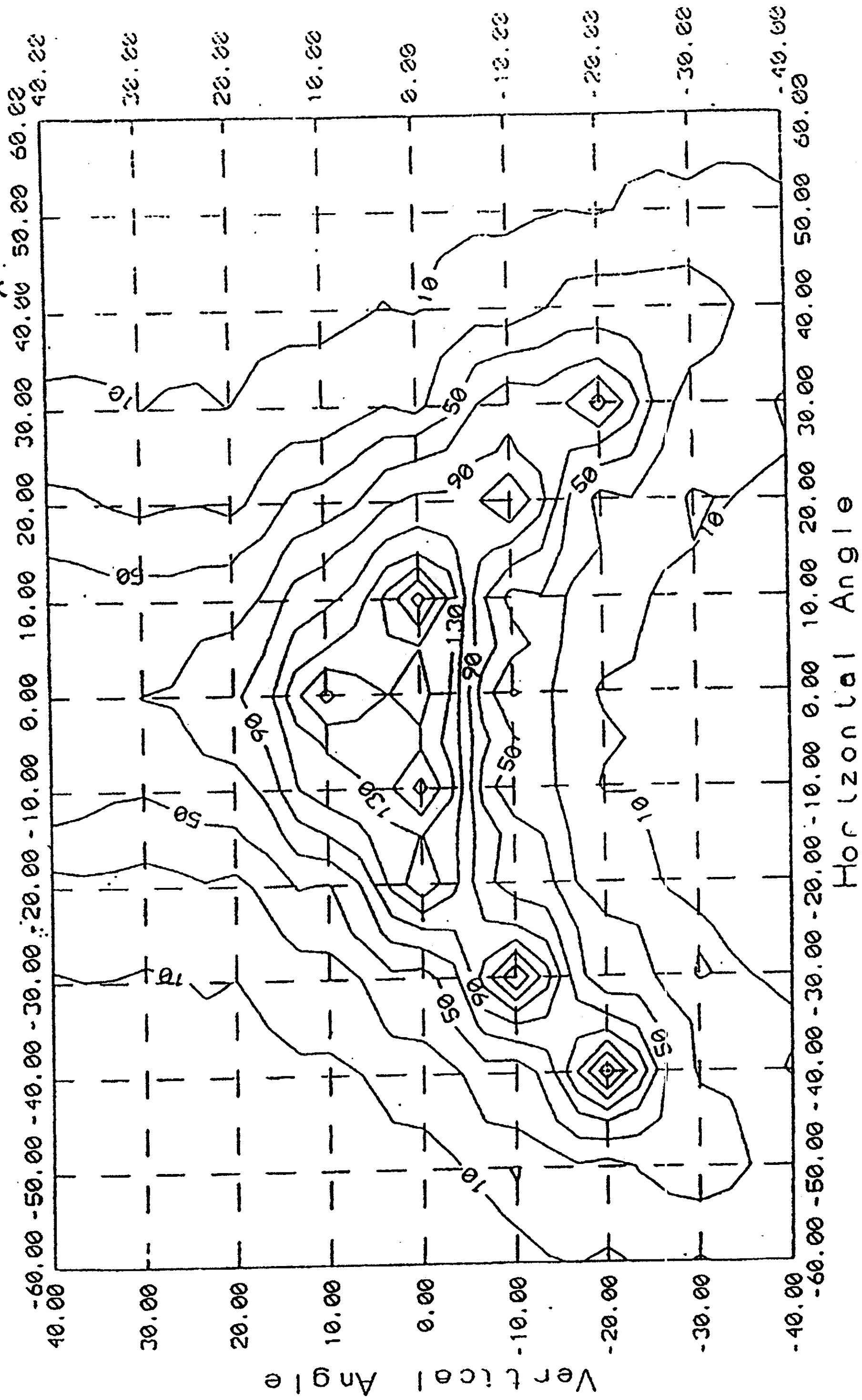


FIG. 1 (PRIOR ART)

$V_{on} = 5.0$ V
R = 0 nm
λ = WHITE

FIG. 2 (PRIOR ART)



R = 0 nm
λ = WHITE

FIG 3 (PRIOR ART)

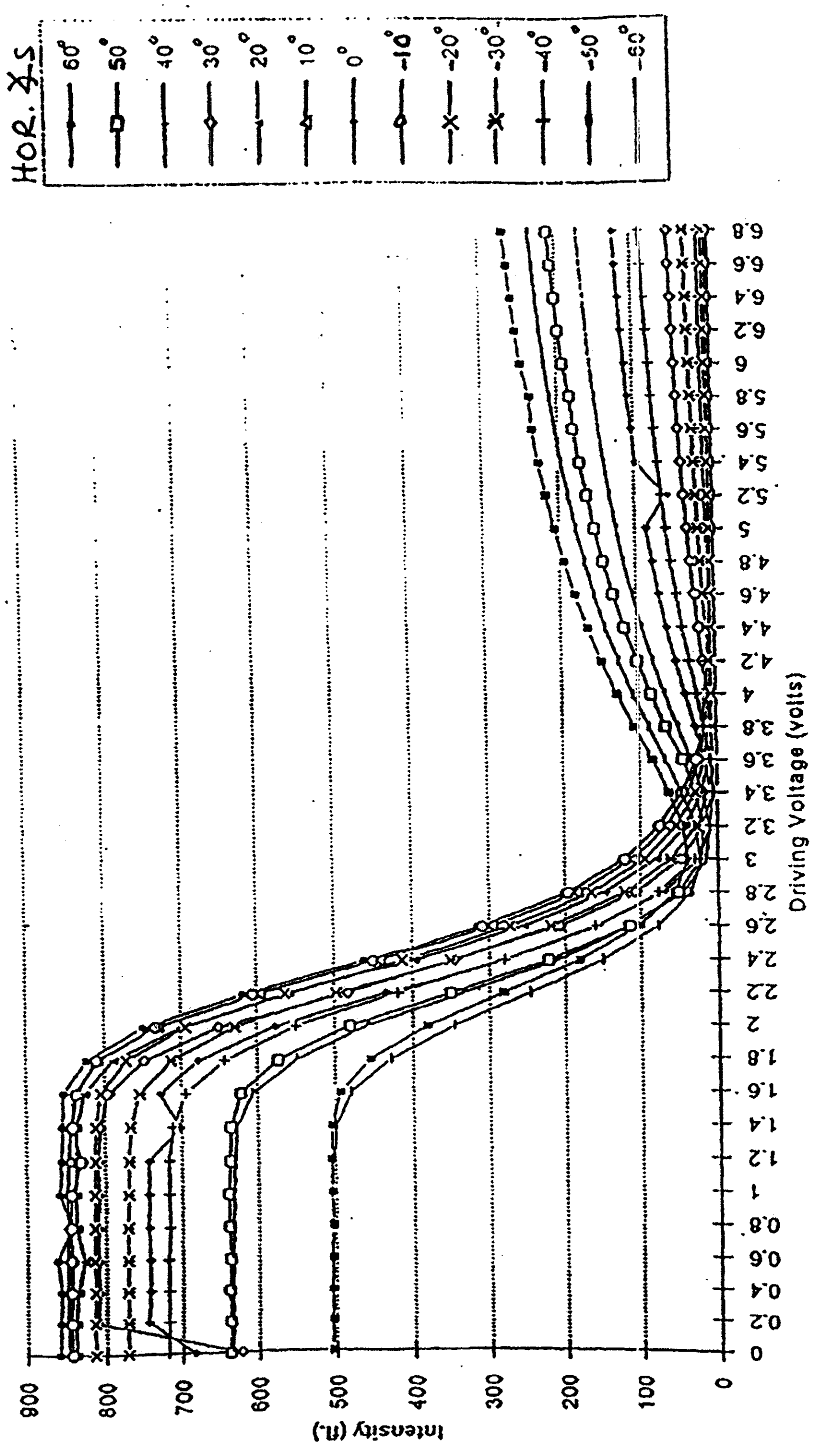
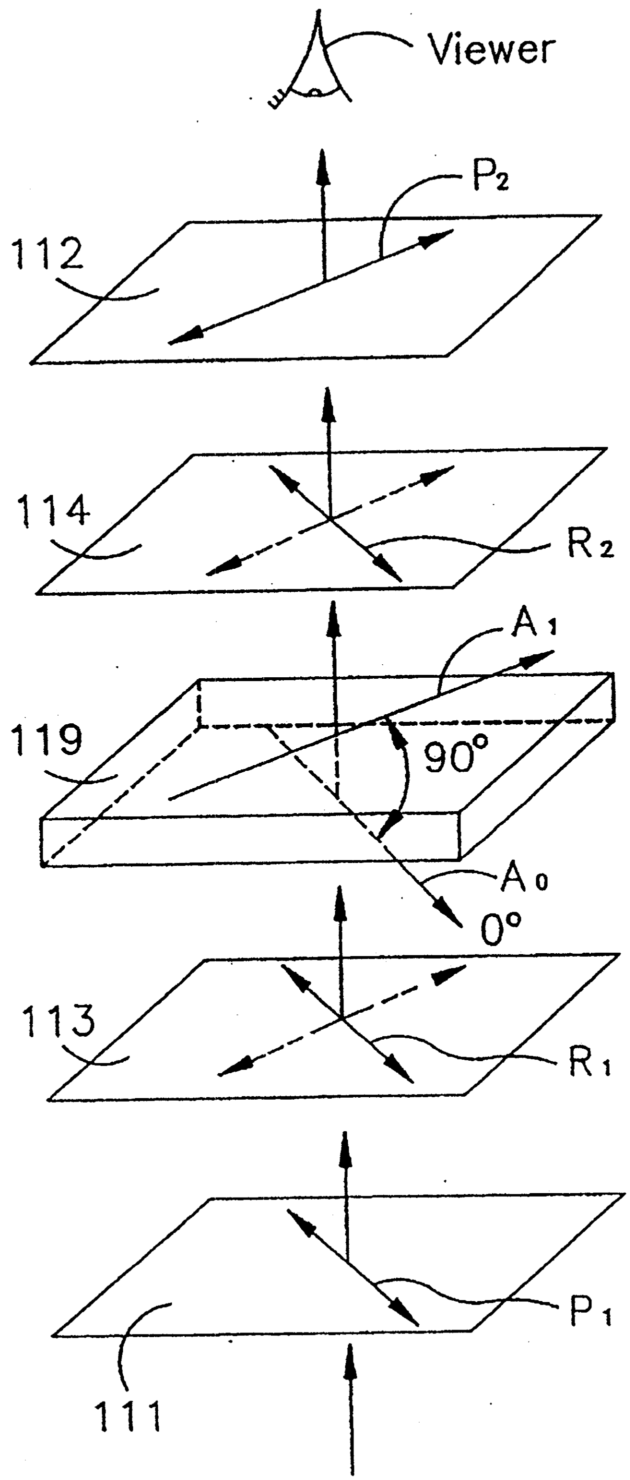


Fig. 4 (Prior Art)



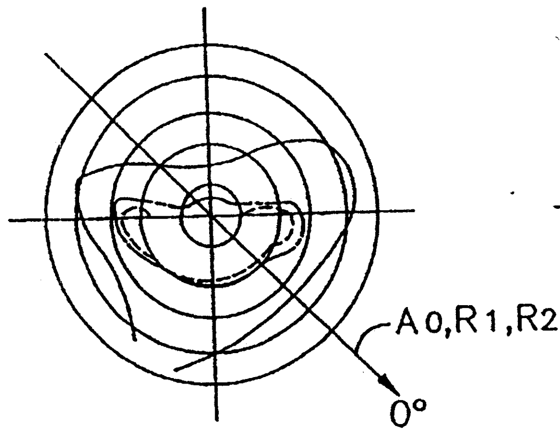


Fig. 5A (Prior Art)

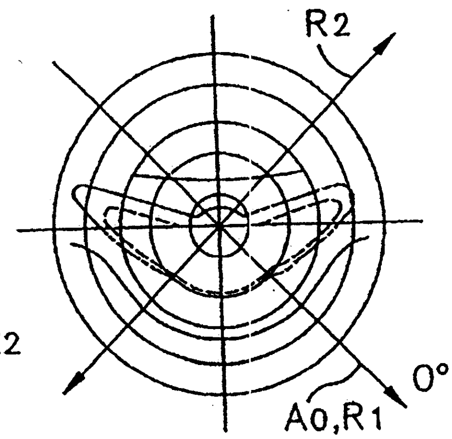


Fig. 5B (Prior Art)

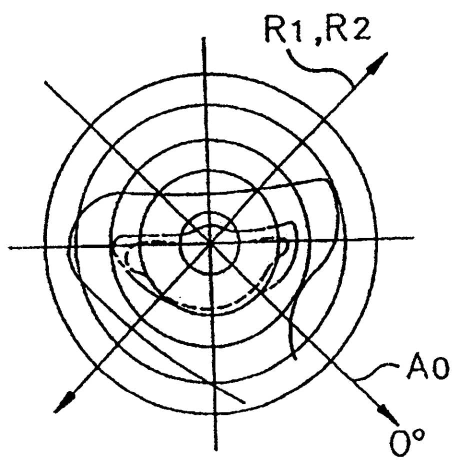


Fig. 5C (Prior Art)

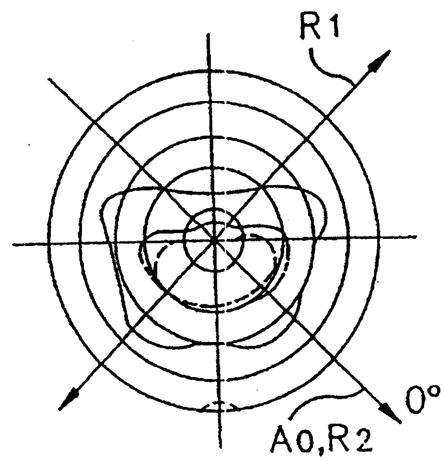


Fig. 5D (Prior Art)

- - - - - - - -	100:1
— - — - —	50:1
————	10:1

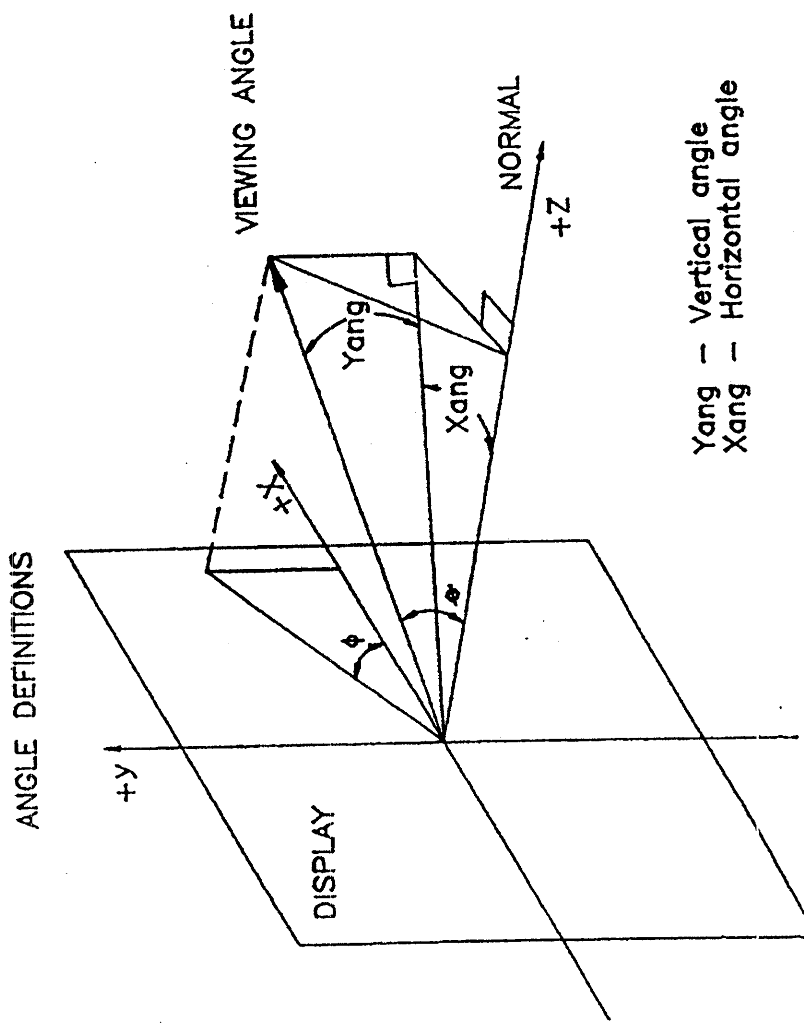
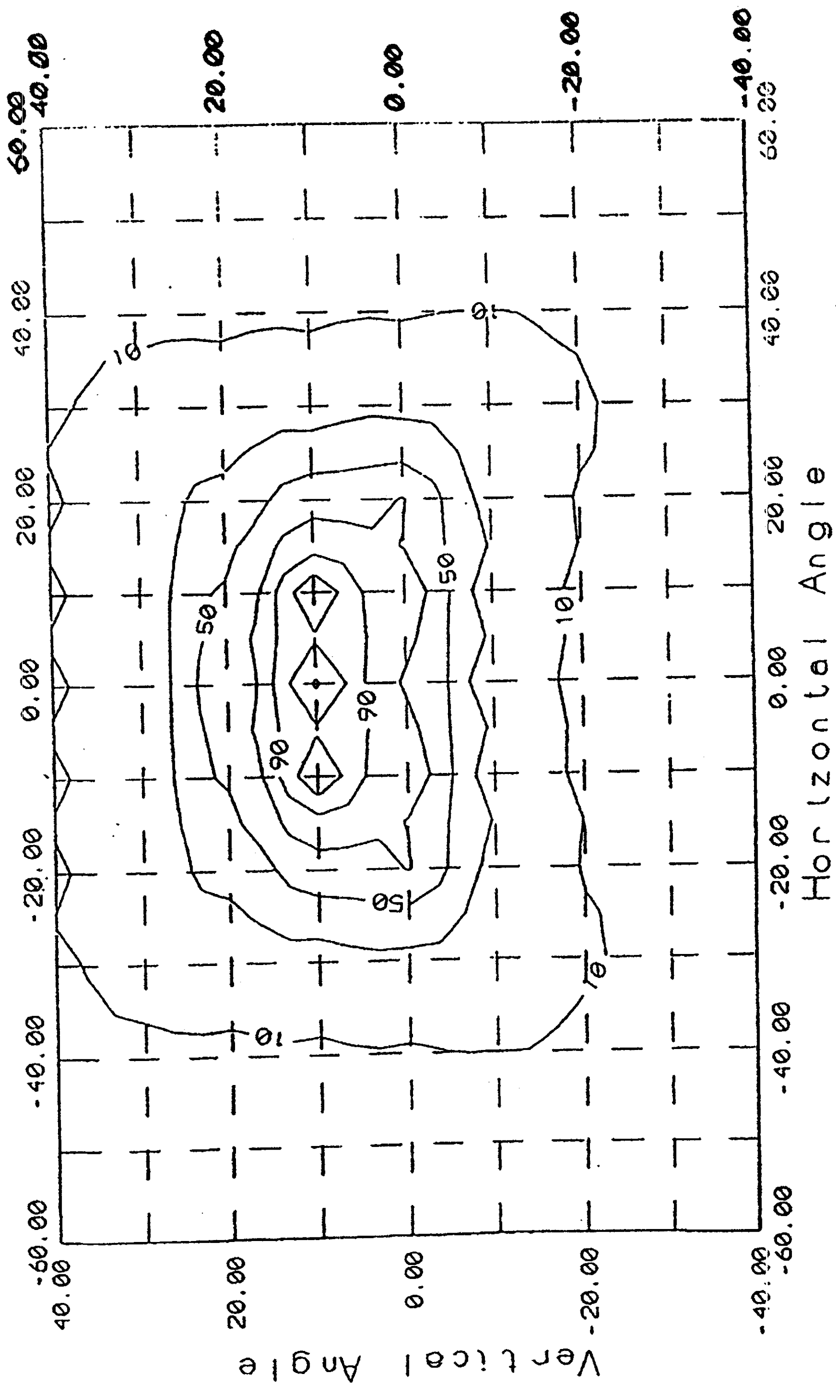

ANGLE DEFINITIONS
VIEWING ANGLE
NORMAL
+Z
+X
+y
DISPLAY
Yang
Xang
Yang – Vertical angle
Xang – Horizontal angle

Fig. 6



$V_{ON} = 6.0$ V
$\lambda = 630$ nm
$R = 320$ nm

FIG. 7

$V_{ON} = 5.0$ V.
$\lambda = 630$ nm
$R = 320$ nm

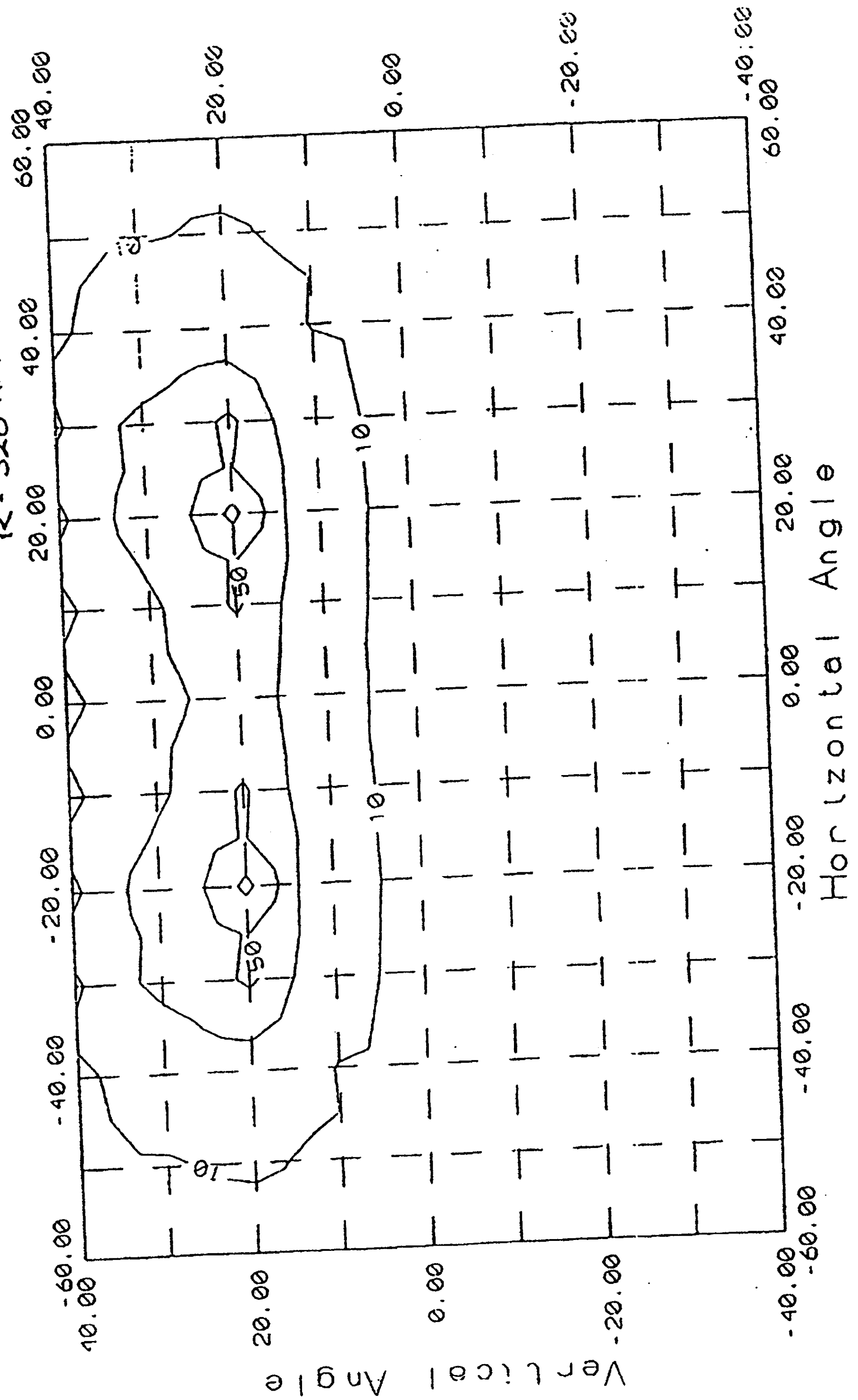


FIG. 8

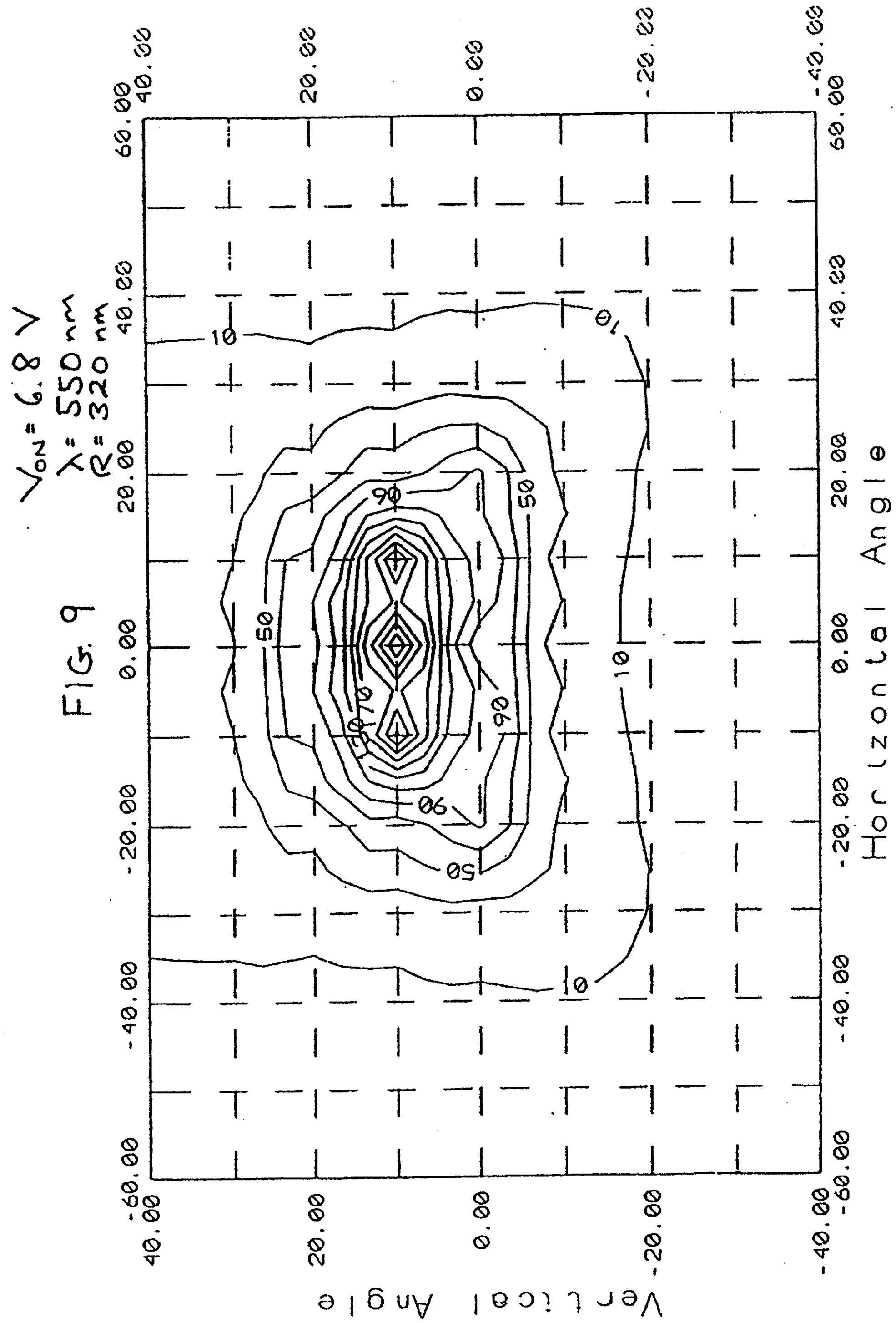

$V_{ON} = 6.8$ V
$\lambda = 550$ nm
$R = 320$ nm
Horizontal Angle
Vertical Angle
10
50
90
70
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00

FIG. 9

$V_{ON} = 6.8\ V$
$\lambda = 480\ nm$
$R = 320\ nm$

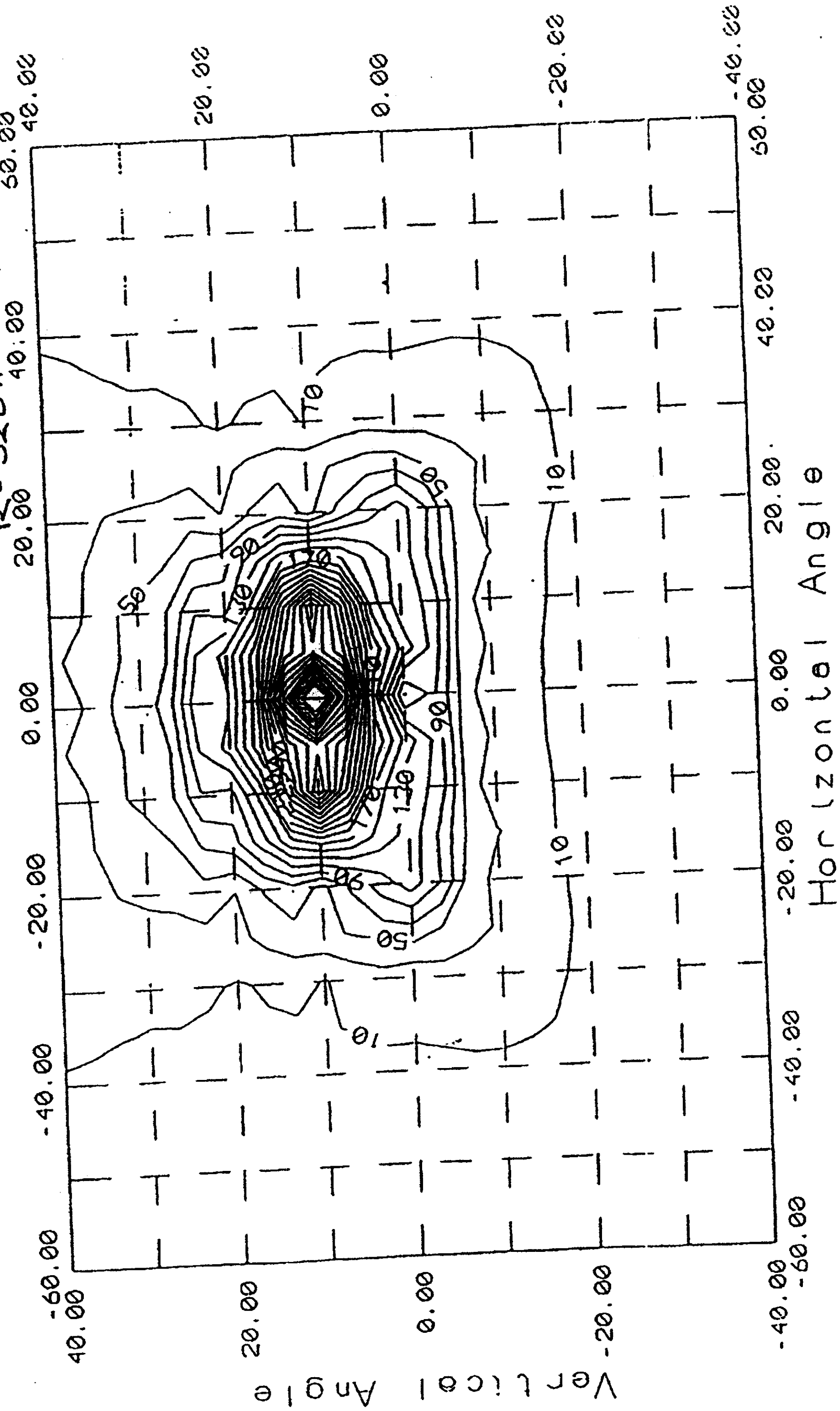
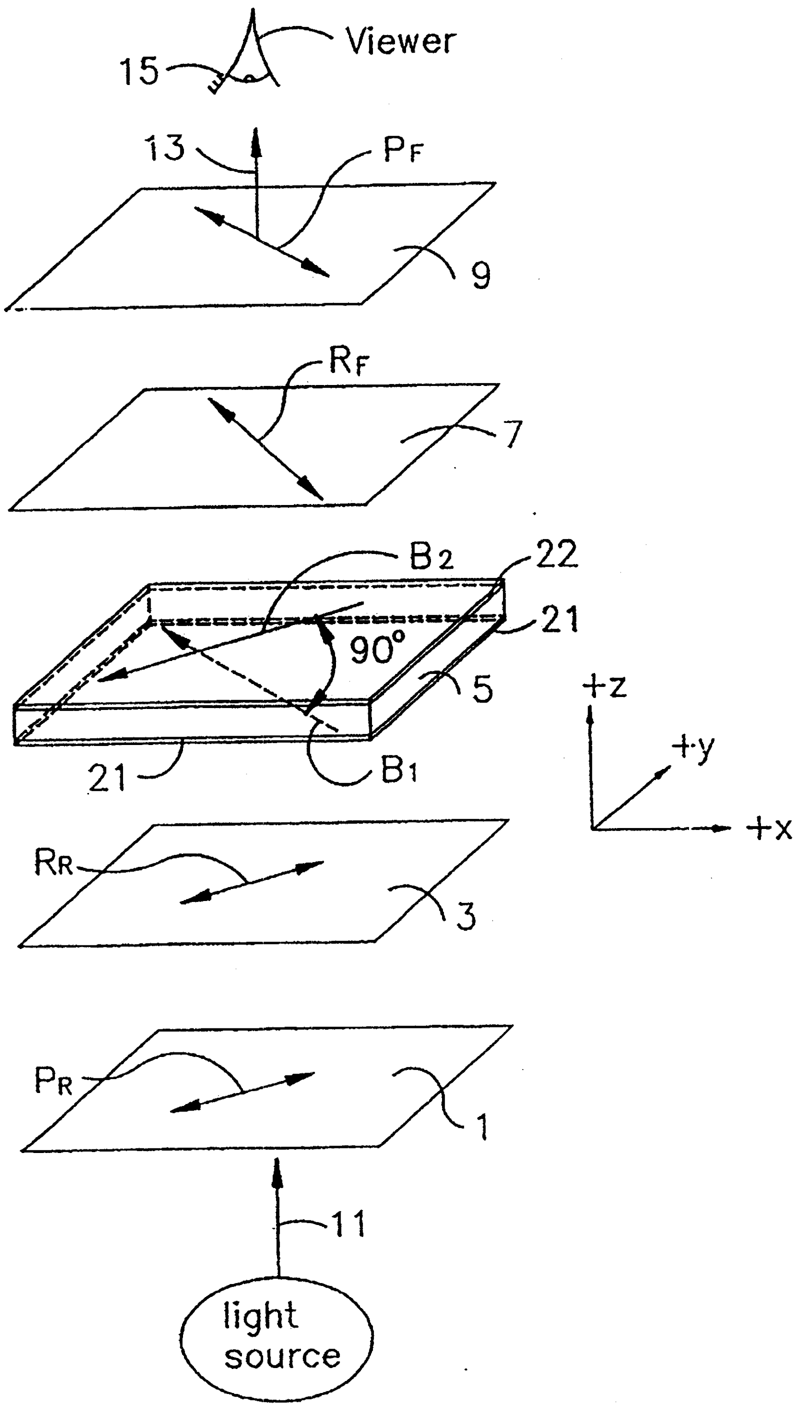


FIG. 10

Fig. 11(a)



Viewer
15
13
PF
9
RF
7
B2
22
21
90°
5
21
B1
+z
+y
+x
RR
3
PR
1
11
light source

Fig. 11(b)

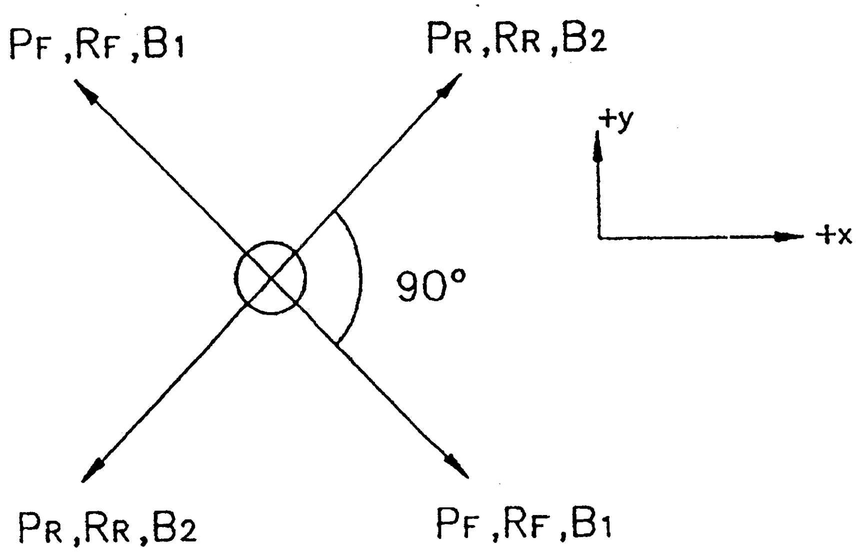
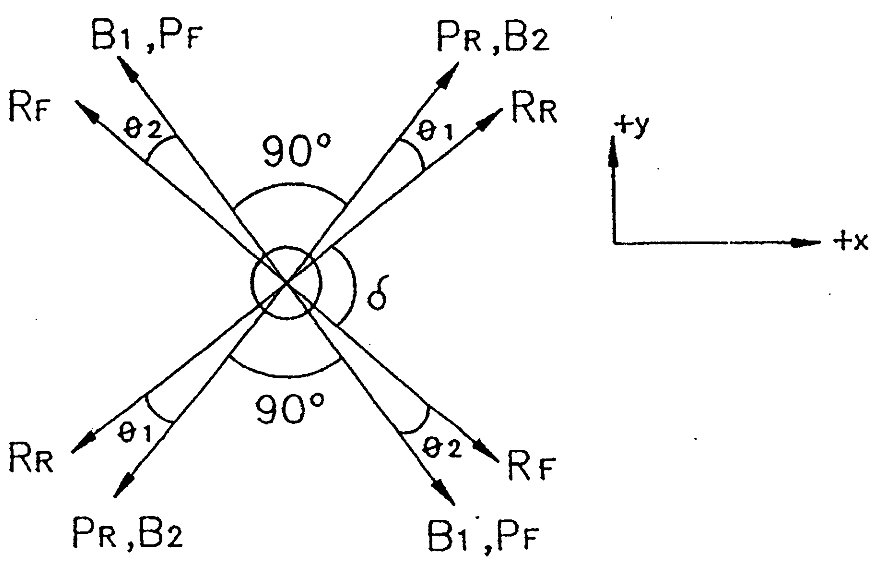


Fig. 11(c)



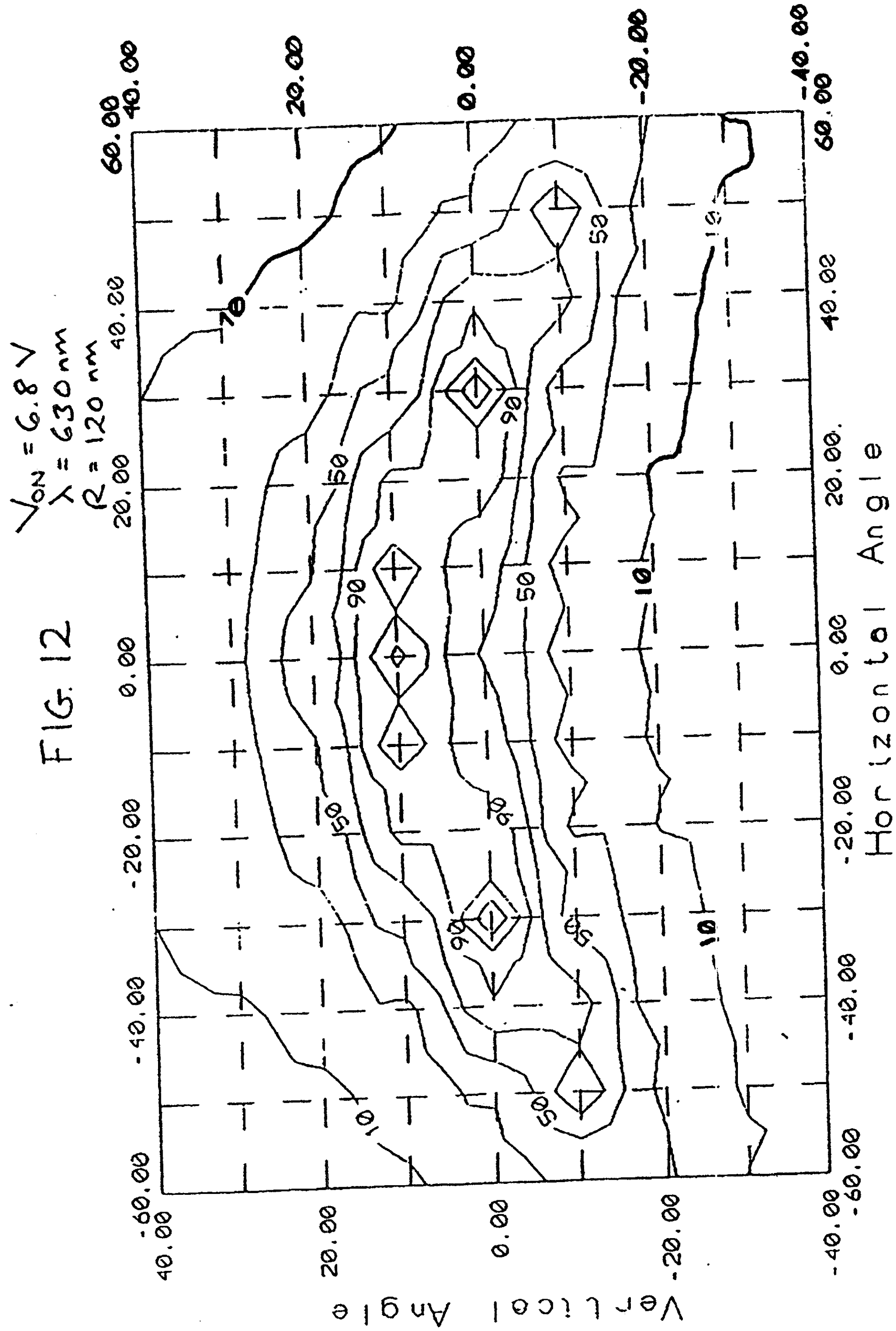
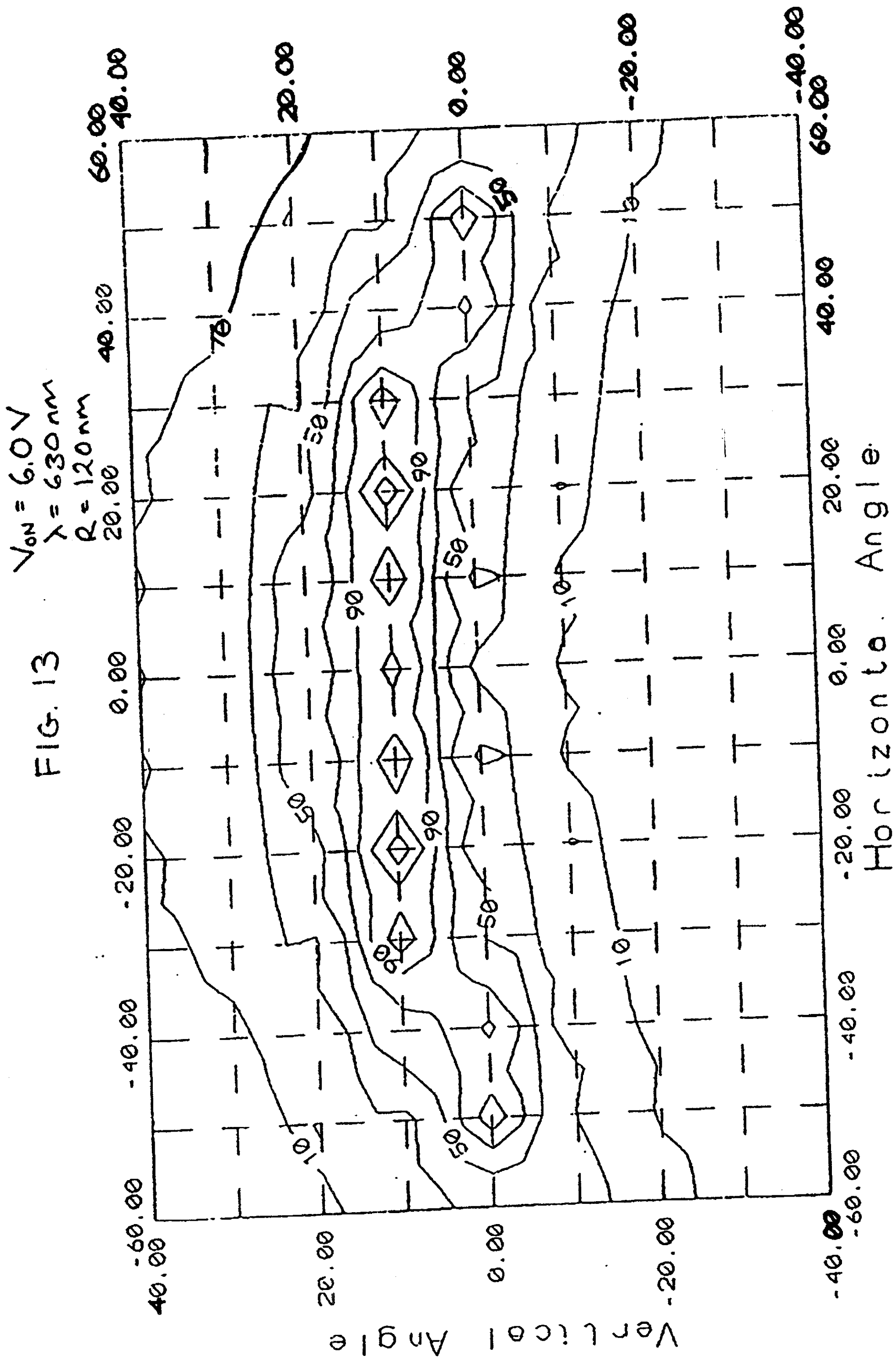


FIG. 12



V_{ON} = 6.0V
λ = 630nm
R = 120nm
Horizontal Angle
Vertical Angle
10
50
70
90

FIG. 13

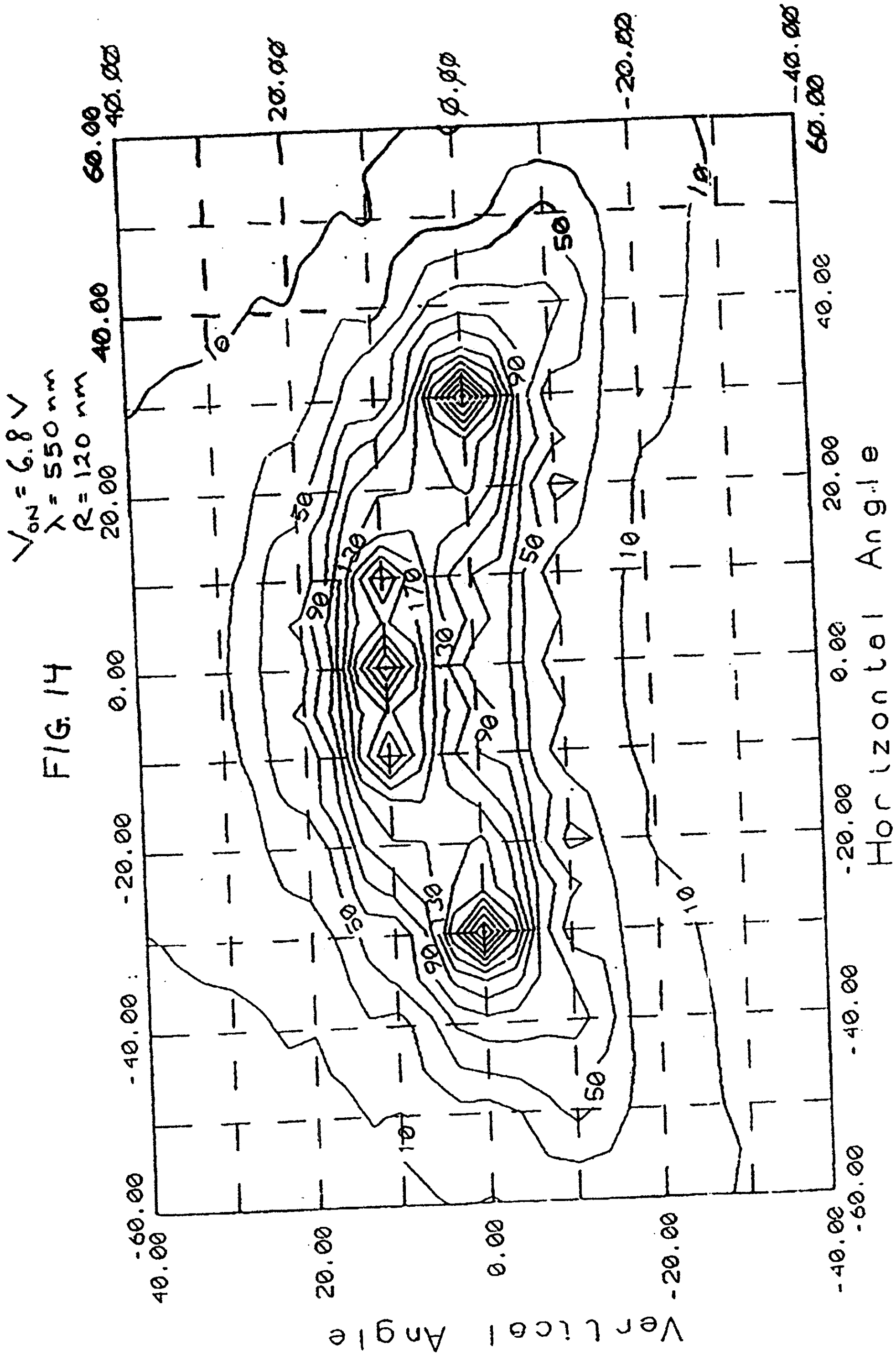


FIG. 14

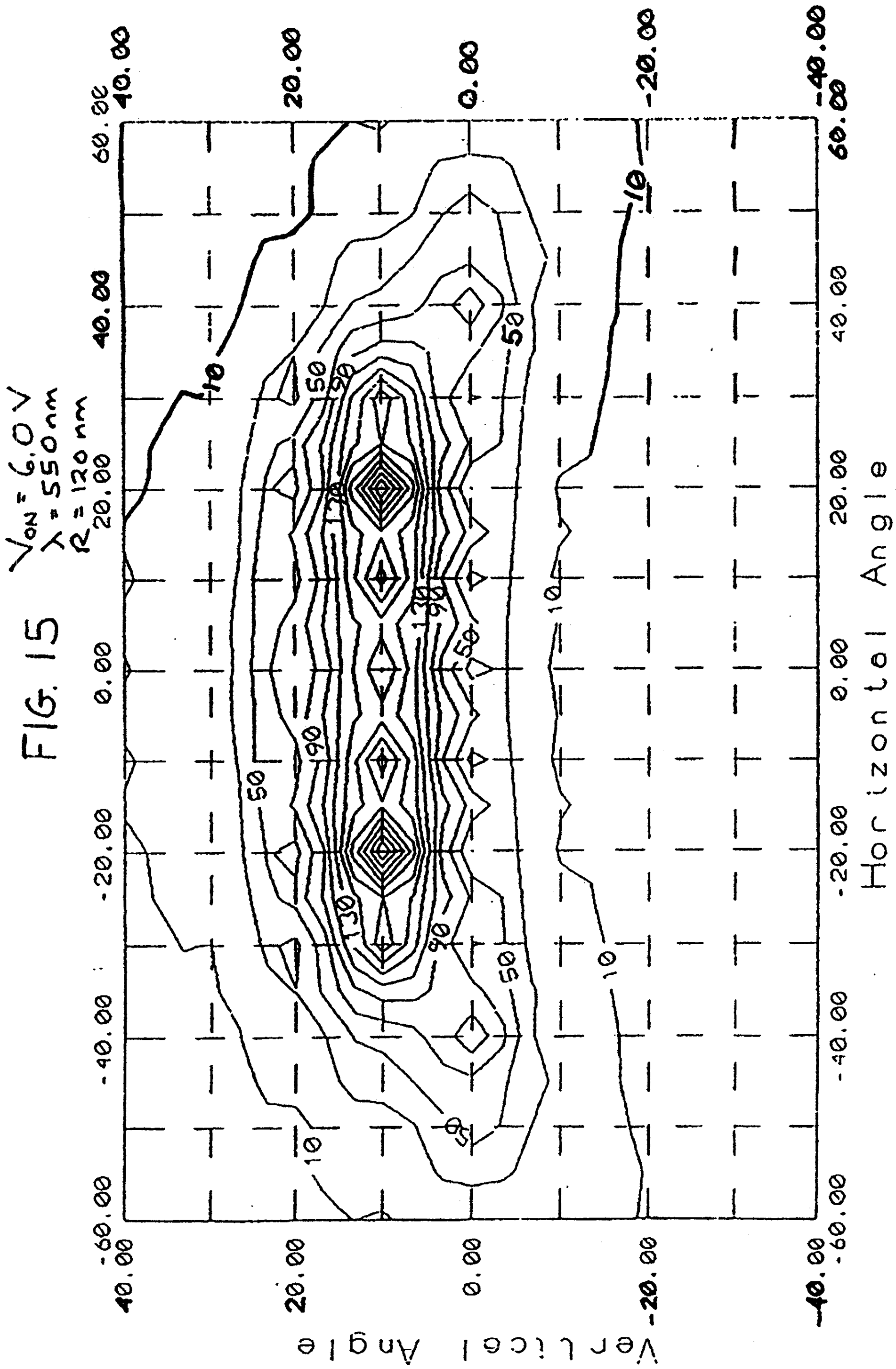

V_{ON} = 6.0 V
λ = 550 nm
R = 120 nm
Horizontal Angle
Vertical Angle
10
50
90
130

FIG. 15

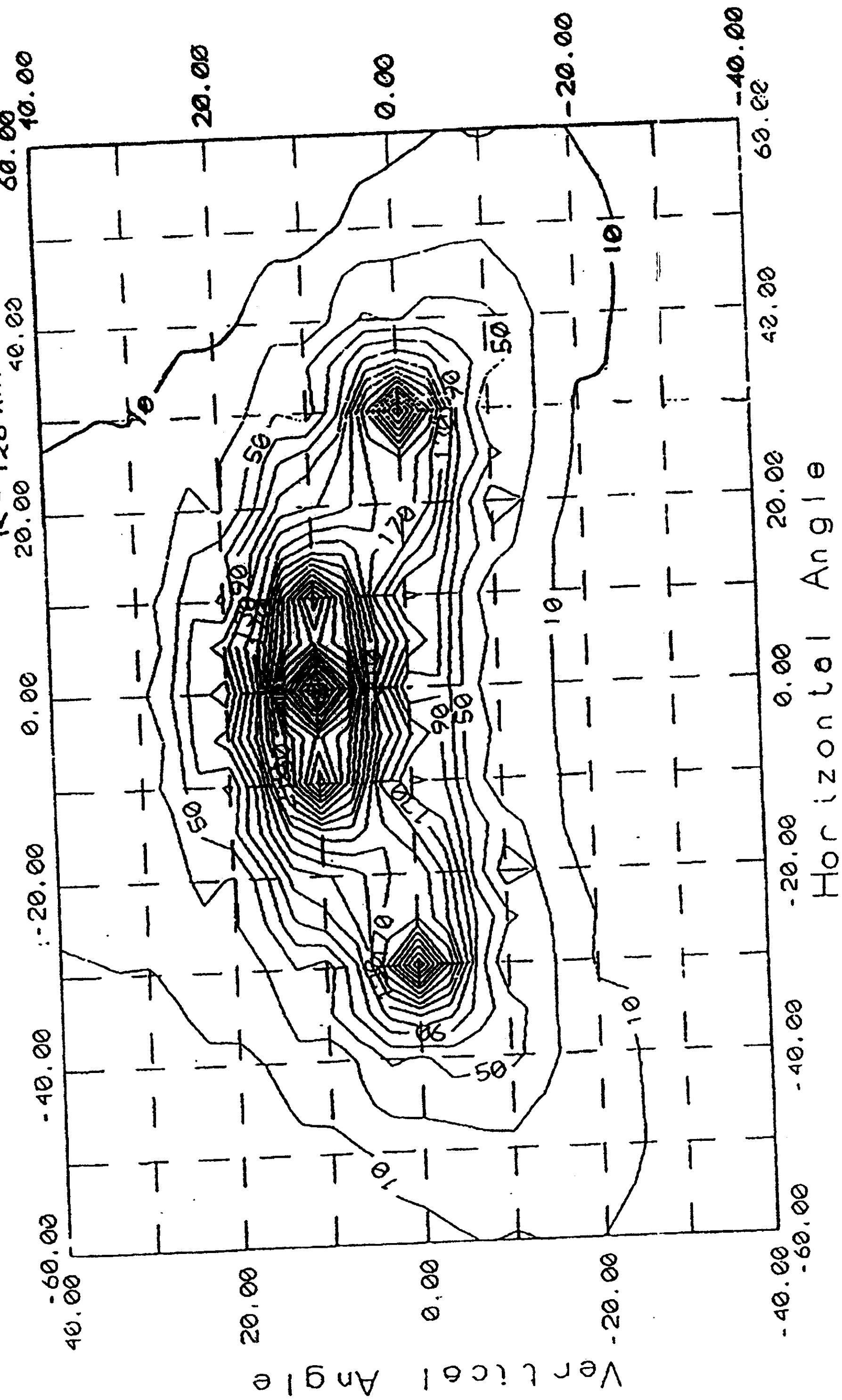
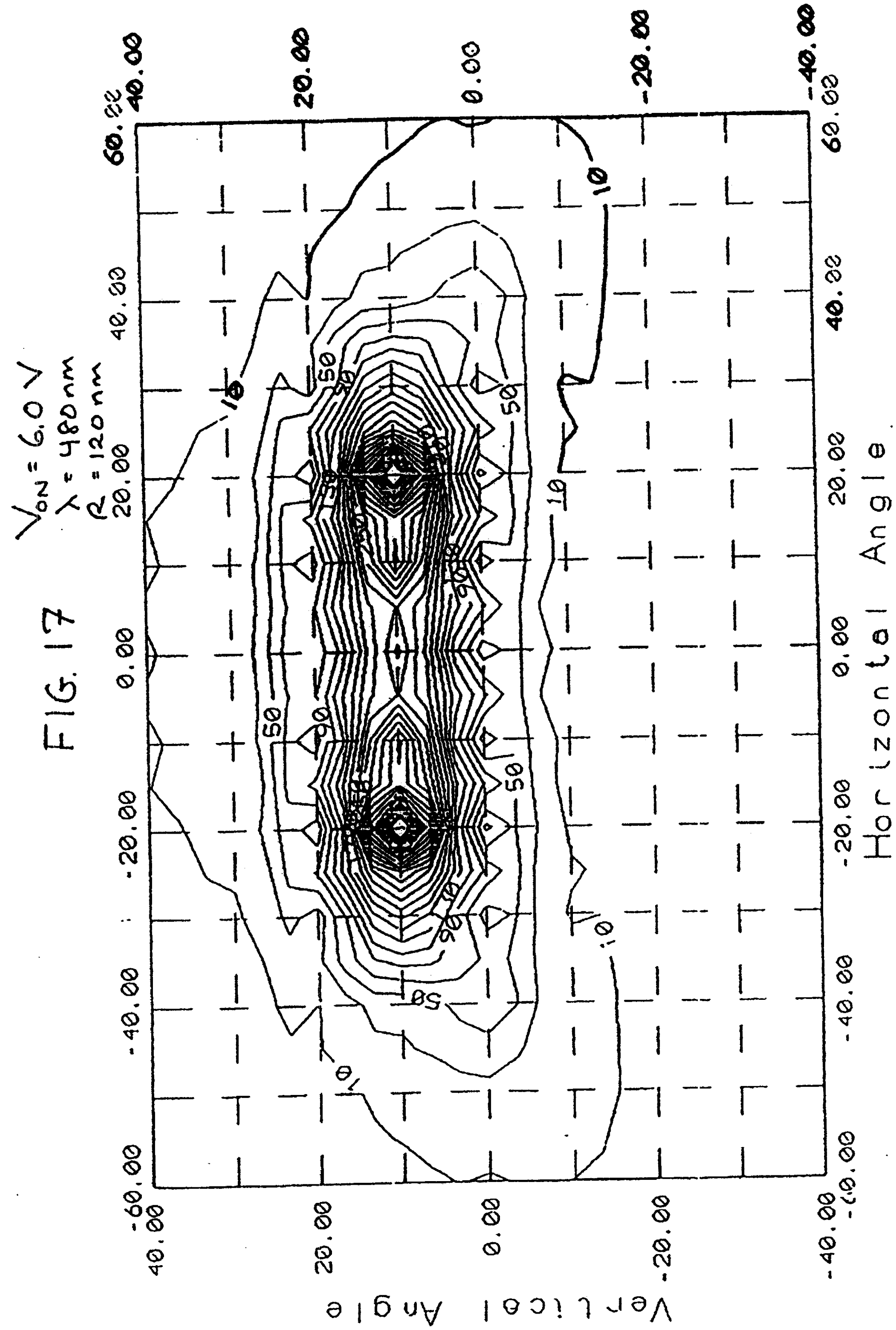


FIG. 16

$V_{ON} = 6.8$ V
$\lambda = 480$ nm
$R = 120$ nm

FIG. 17



V_{ON} = 6.0 V
λ = 480nm
R = 120nm
Horizontal Angle
Vertical Angle
10
50
90

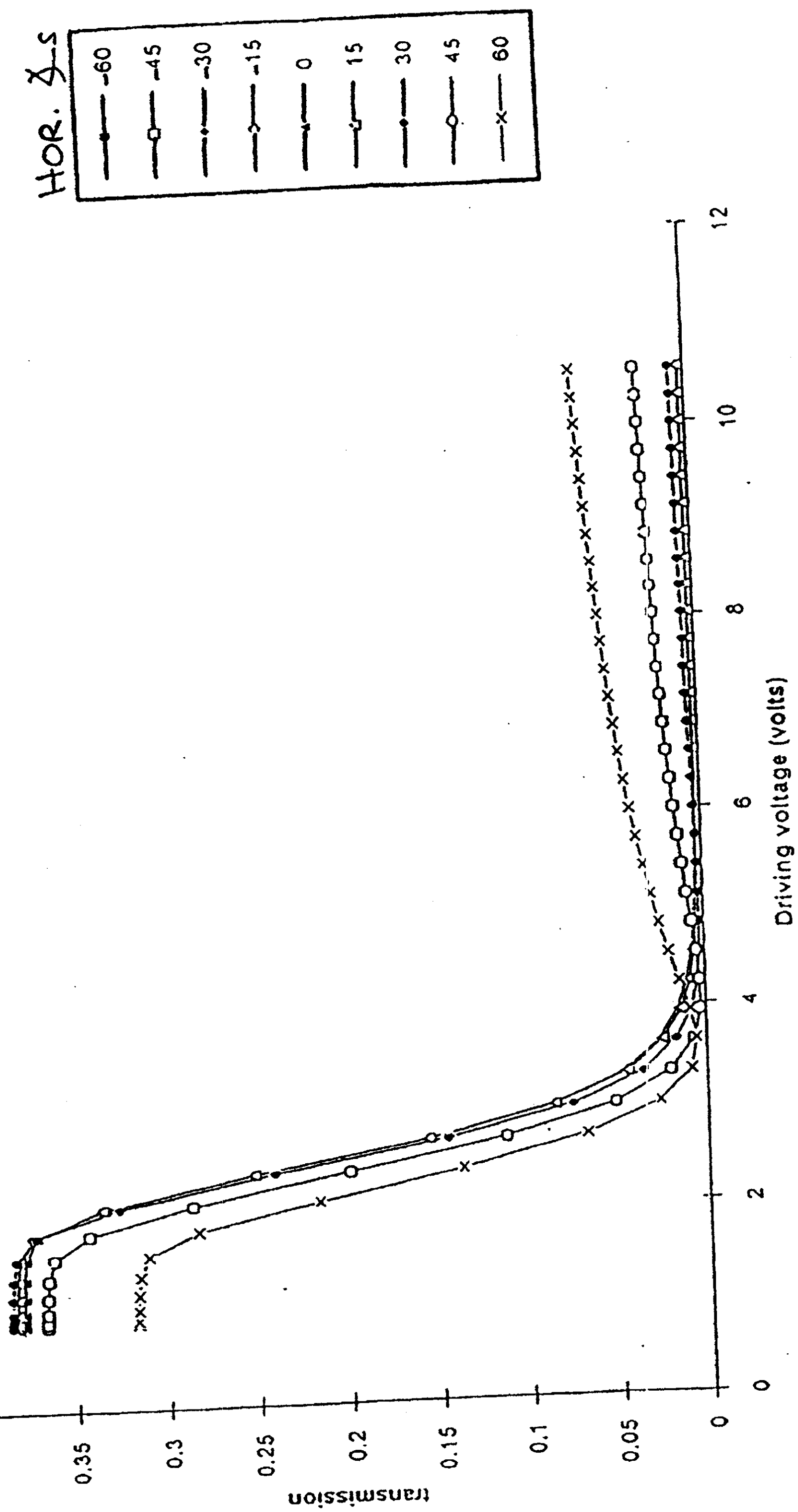

HOR. ∡s
-60
-45
-30
-15
0
15
30
45
60
transmission
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Driving voltage (volts)
0
2
4
6
8
10
12

FIG. 18

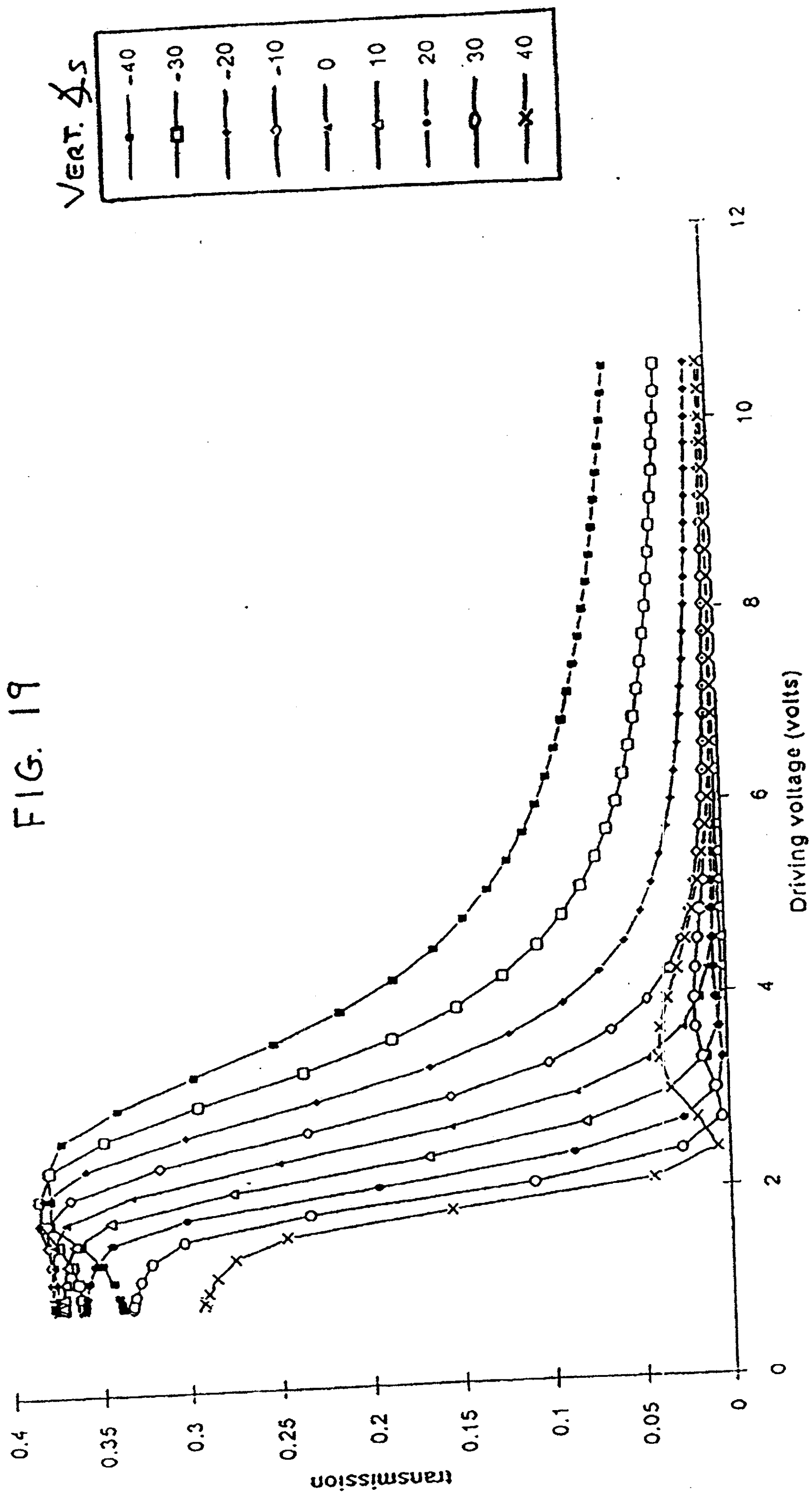

VERT. ∆s
-40
-30
-20
-10
0
10
20
30
40
transmission
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Driving voltage (volts)
0
2
4
6
8
10
12

FIG. 19

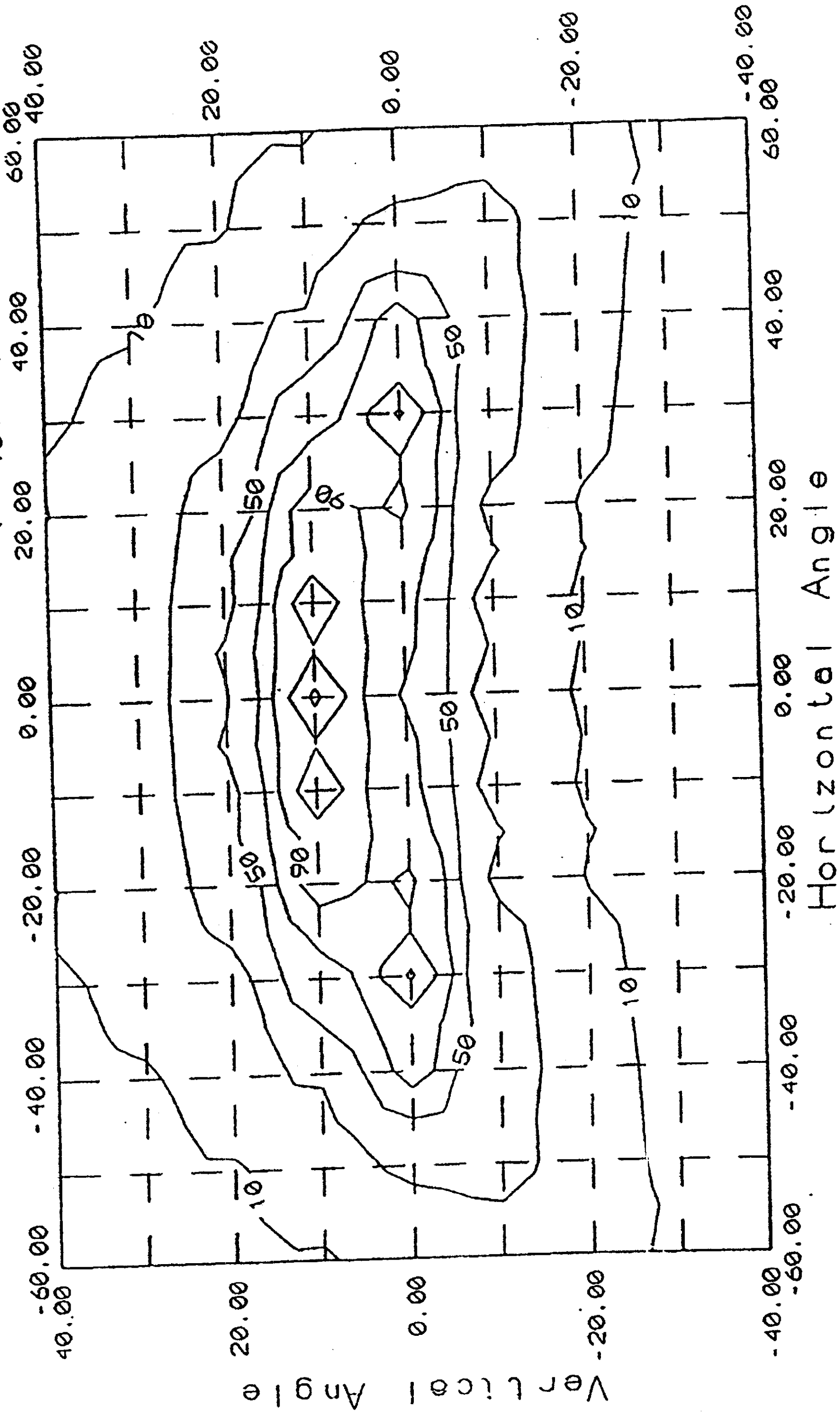


FIG. 20

$V_{ON} = 6.8V$
$\lambda = 630nm$
$R = 160nm$

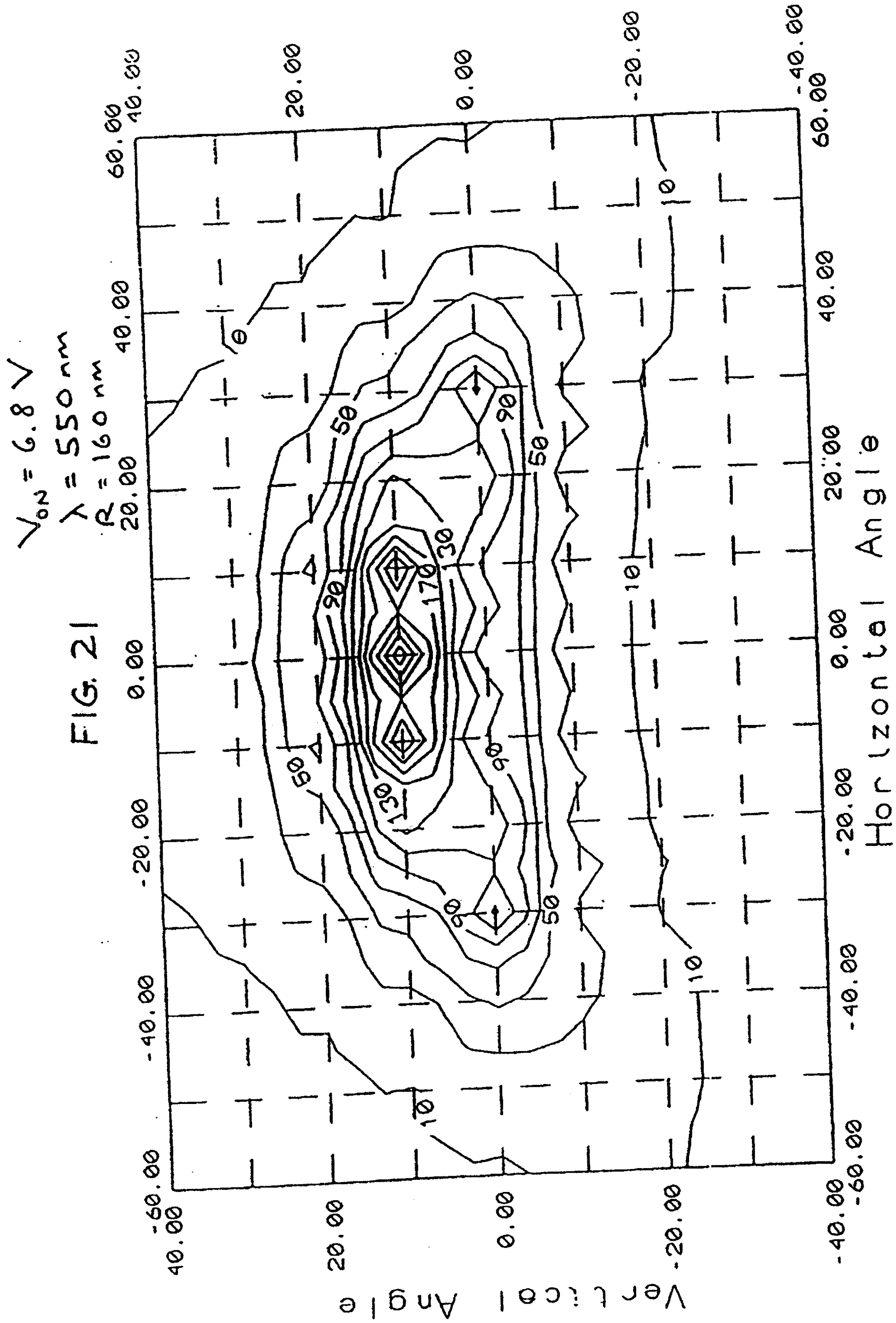
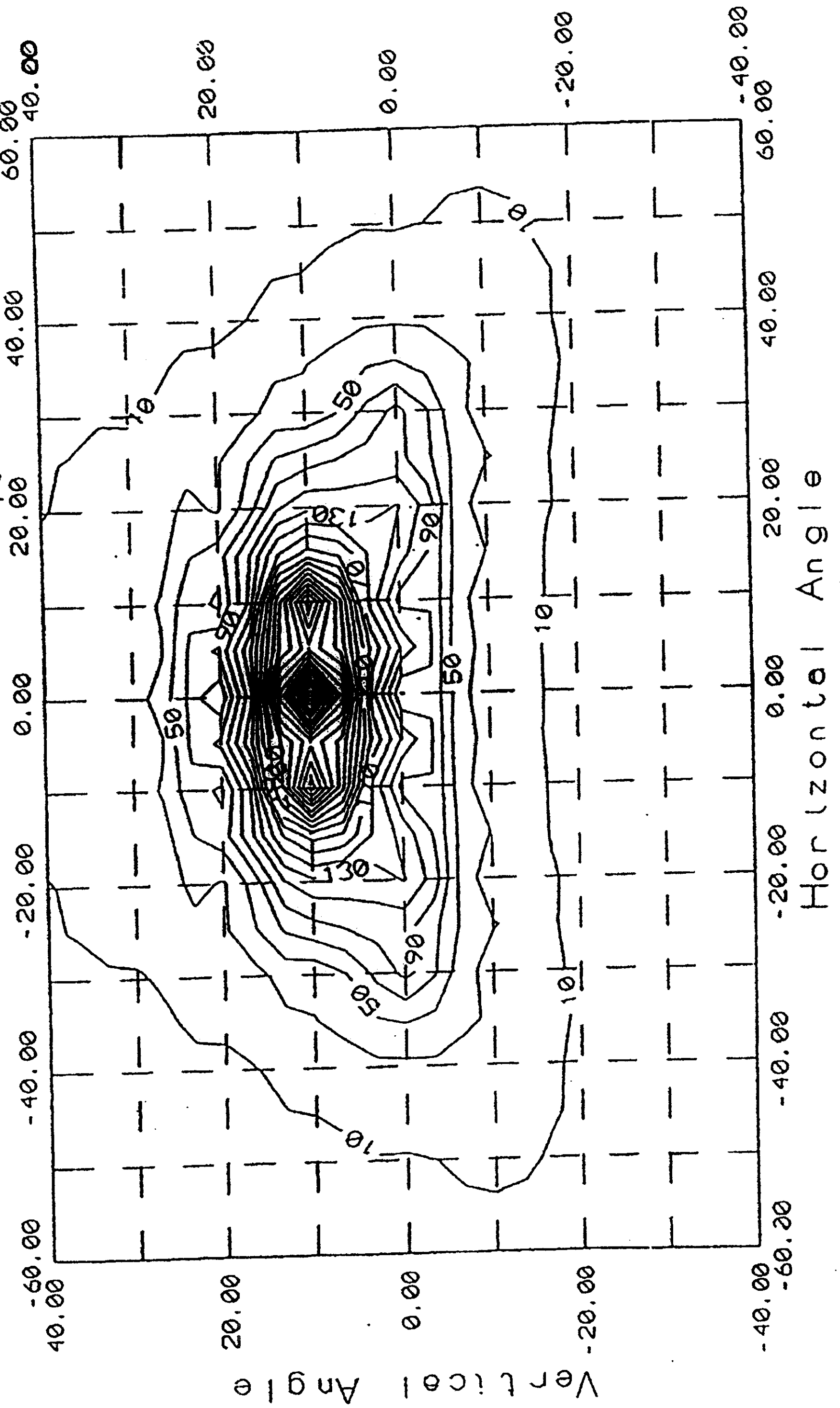
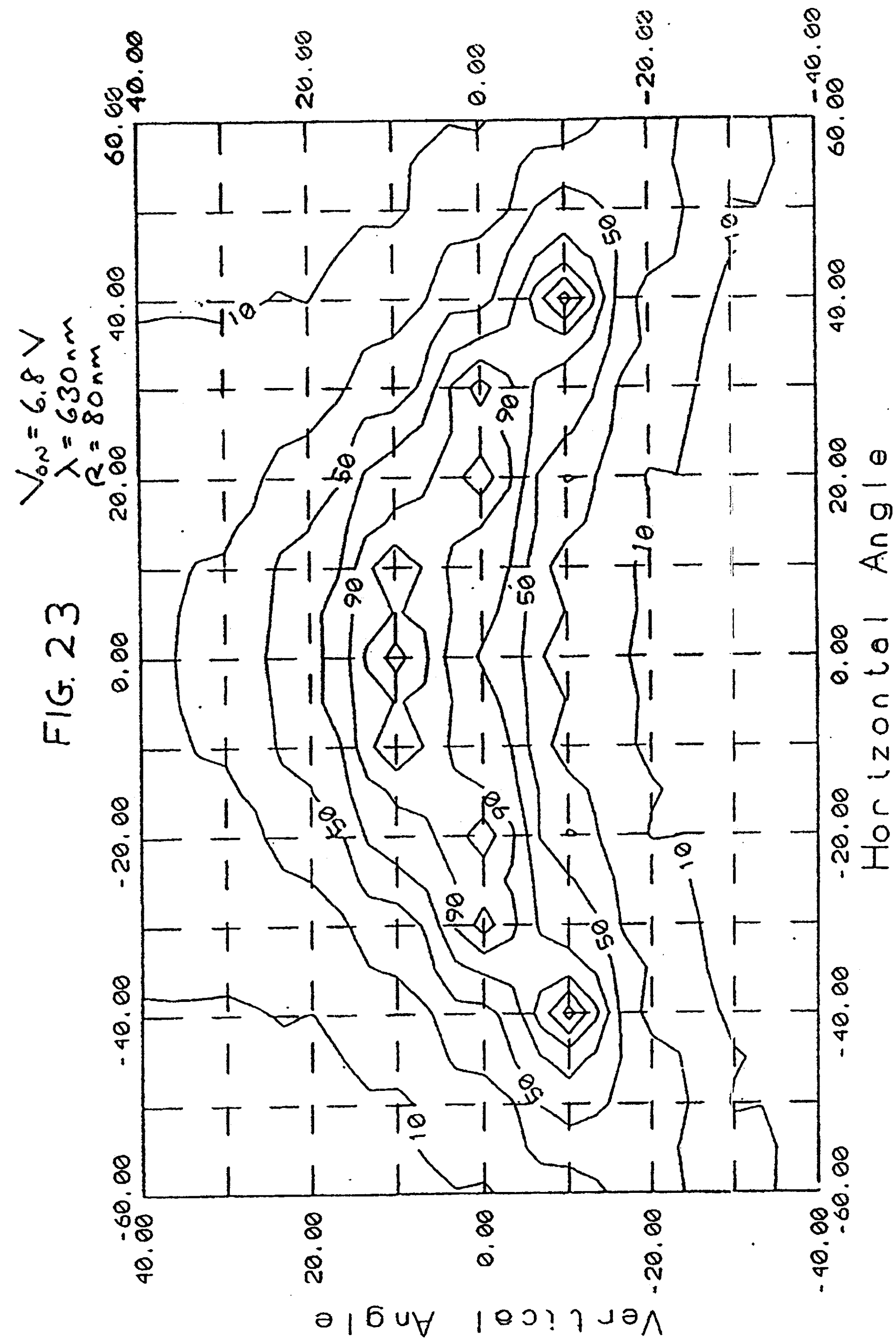


FIG. 21

FIG. 22

$V_{on} = 6.8\,V$
$\lambda = 480\,nm$
$R = 160\,nm$





V_{on} = 6.8 V
λ = 630 nm
R = 80 nm
Horizontal Angle
Vertical Angle
10
50
90

FIG. 23

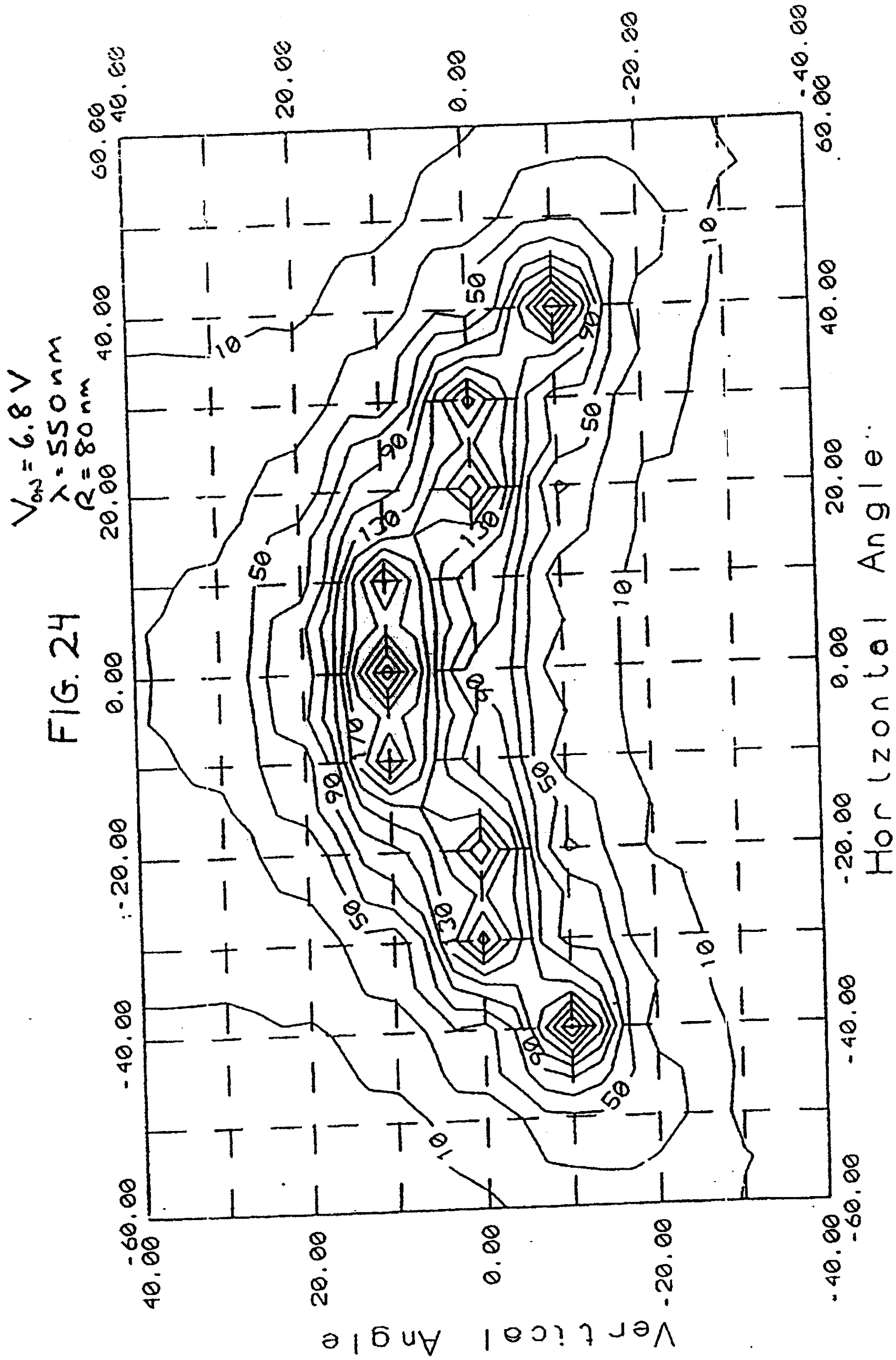

V_{out} = 6.8 V
λ = 550 nm
R = 80 nm
Horizontal Angle
Vertical Angle
10
50
90
130
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00

FIG. 24

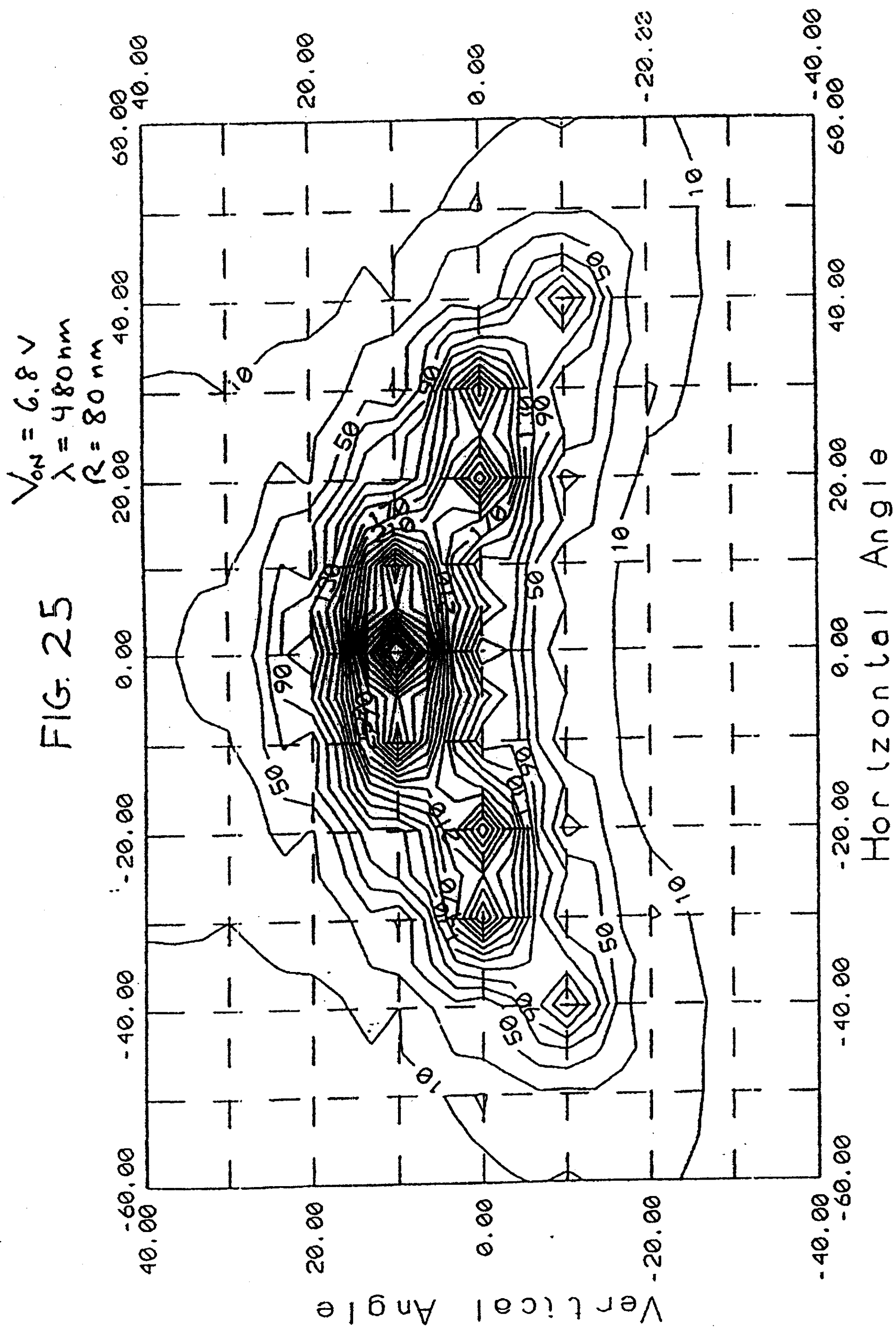
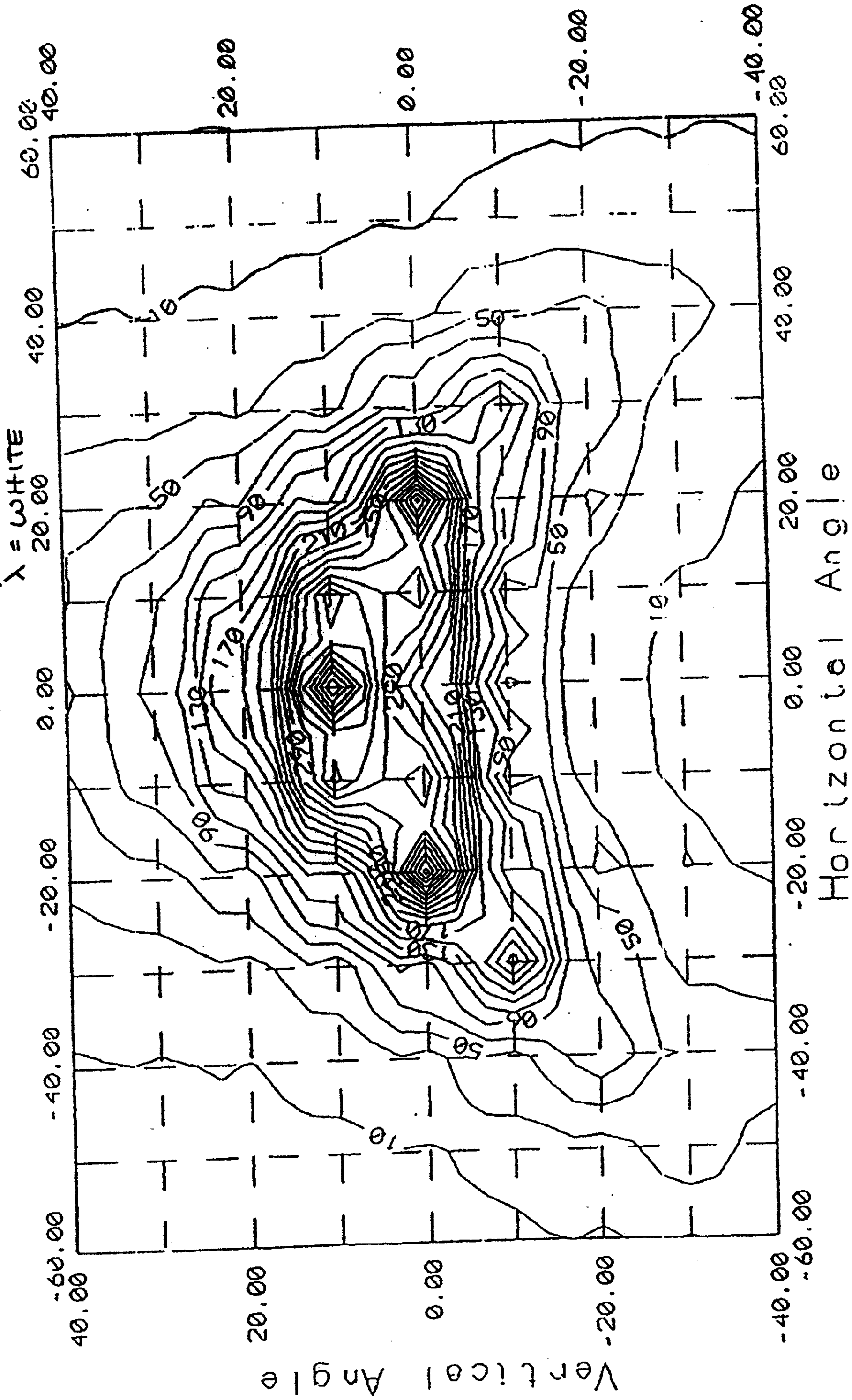

V_{ON} = 6.8 V
λ = 480 nm
R = 80 nm
Horizontal Angle
Vertical Angle
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
10
50
90

FIG. 25

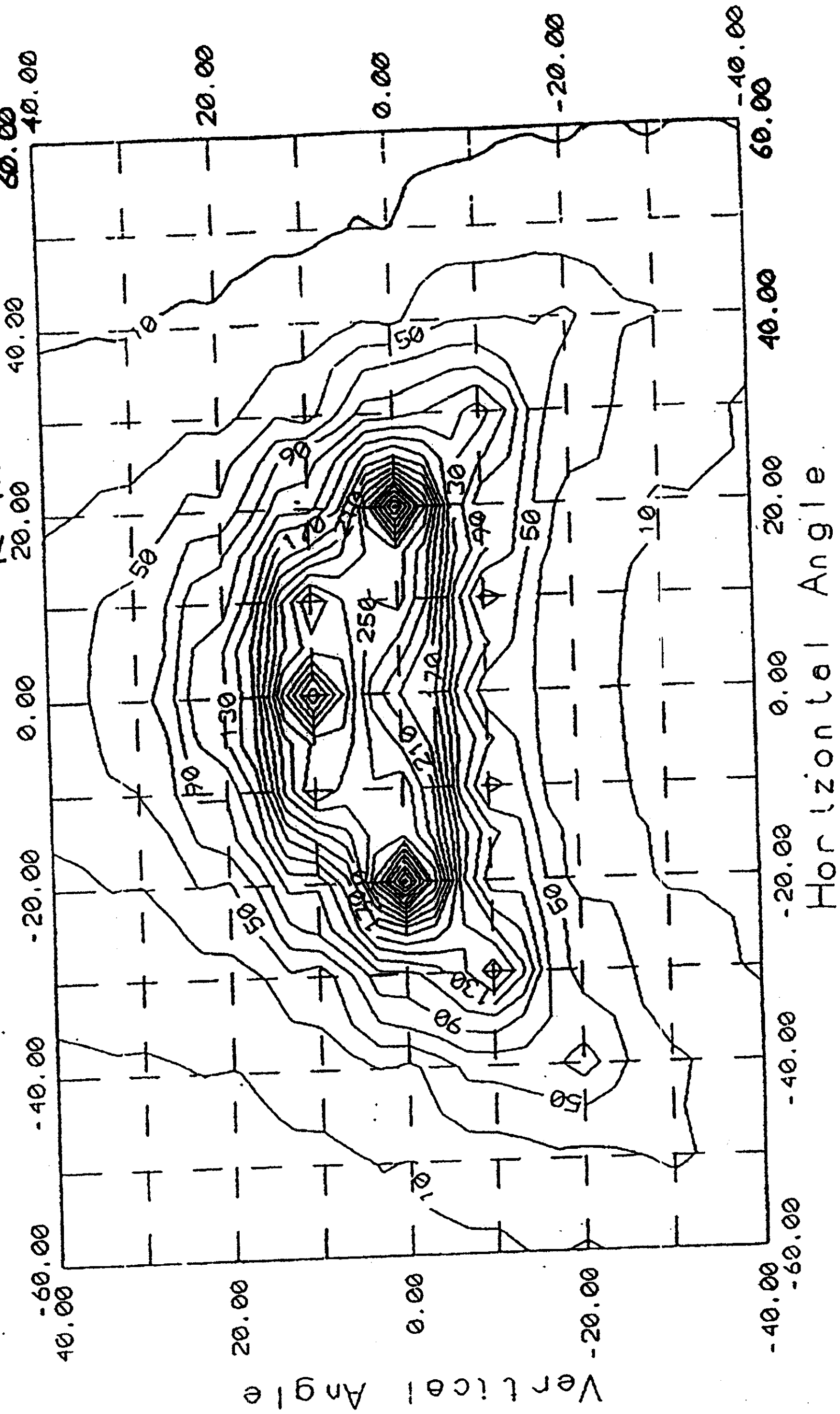


V_{ON} = 6.8 V
R = 120 nm
λ = WHITE
Horizontal Angle
Vertical Angle
10
50
90
130
170
210
250

FIG. 26

FIG. 27

$V_{ON} = 6.0$ V
λ = WHITE
Ω = 120 nm



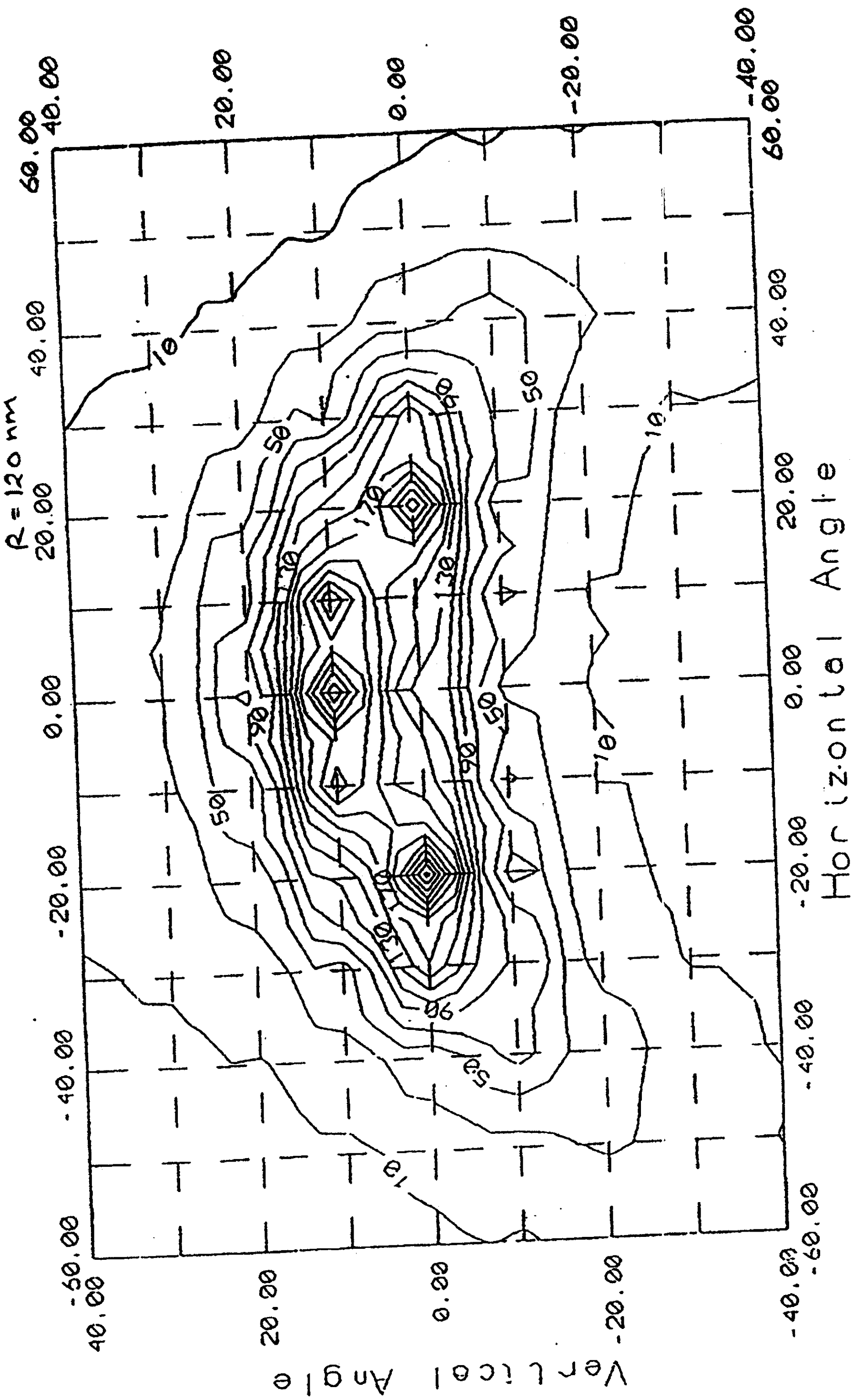

V_{ON} = 5.0 V
λ = WHITE
R = 120 nm
Horizontal Angle
Vertical Angle
40.00
20.00
0.00
-20.00
-40.00
60.00
-60.00
10
50
90
130
170

FIG. 28

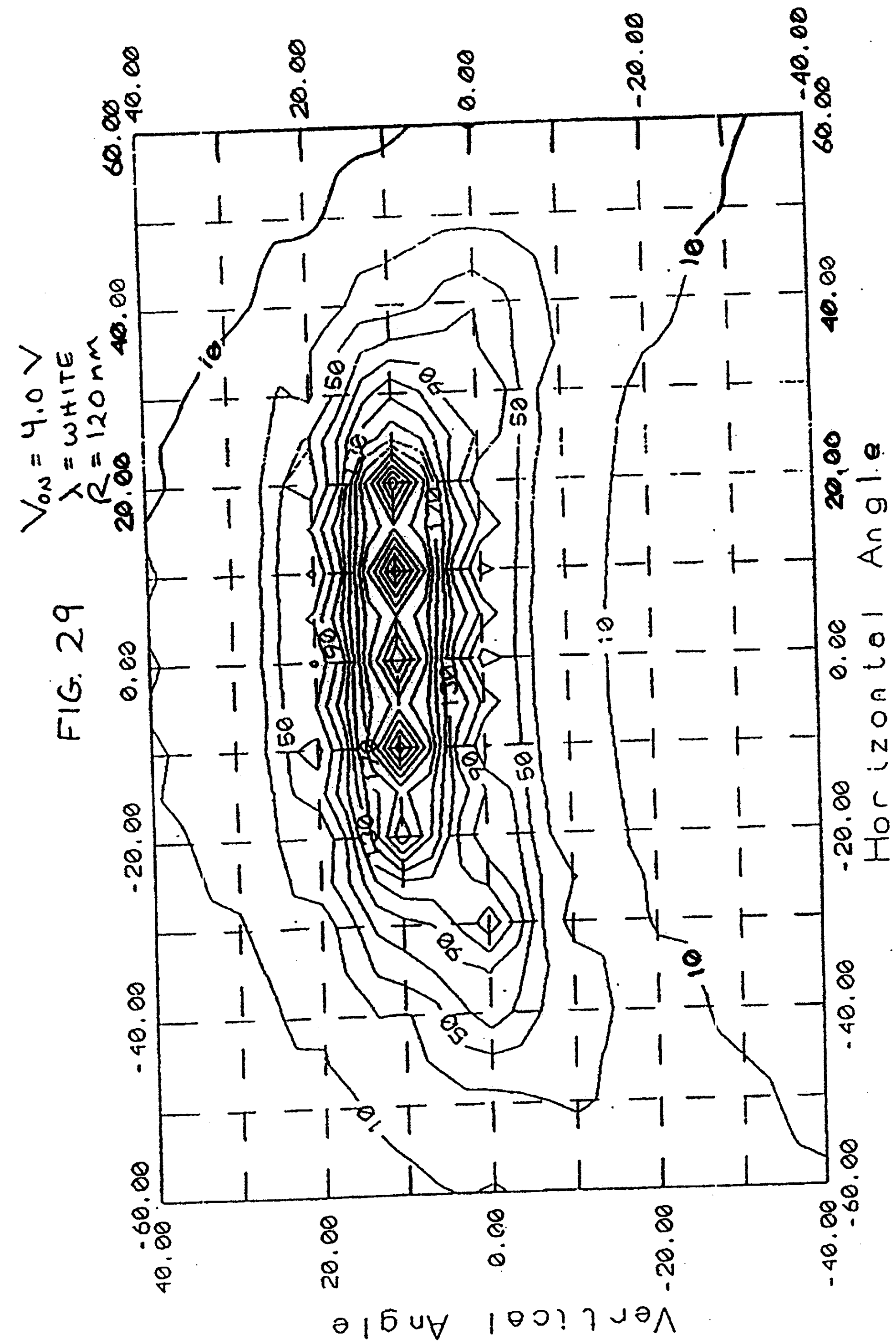


FIG. 29

FIG. 30

R = 120 nm
λ = WHITE

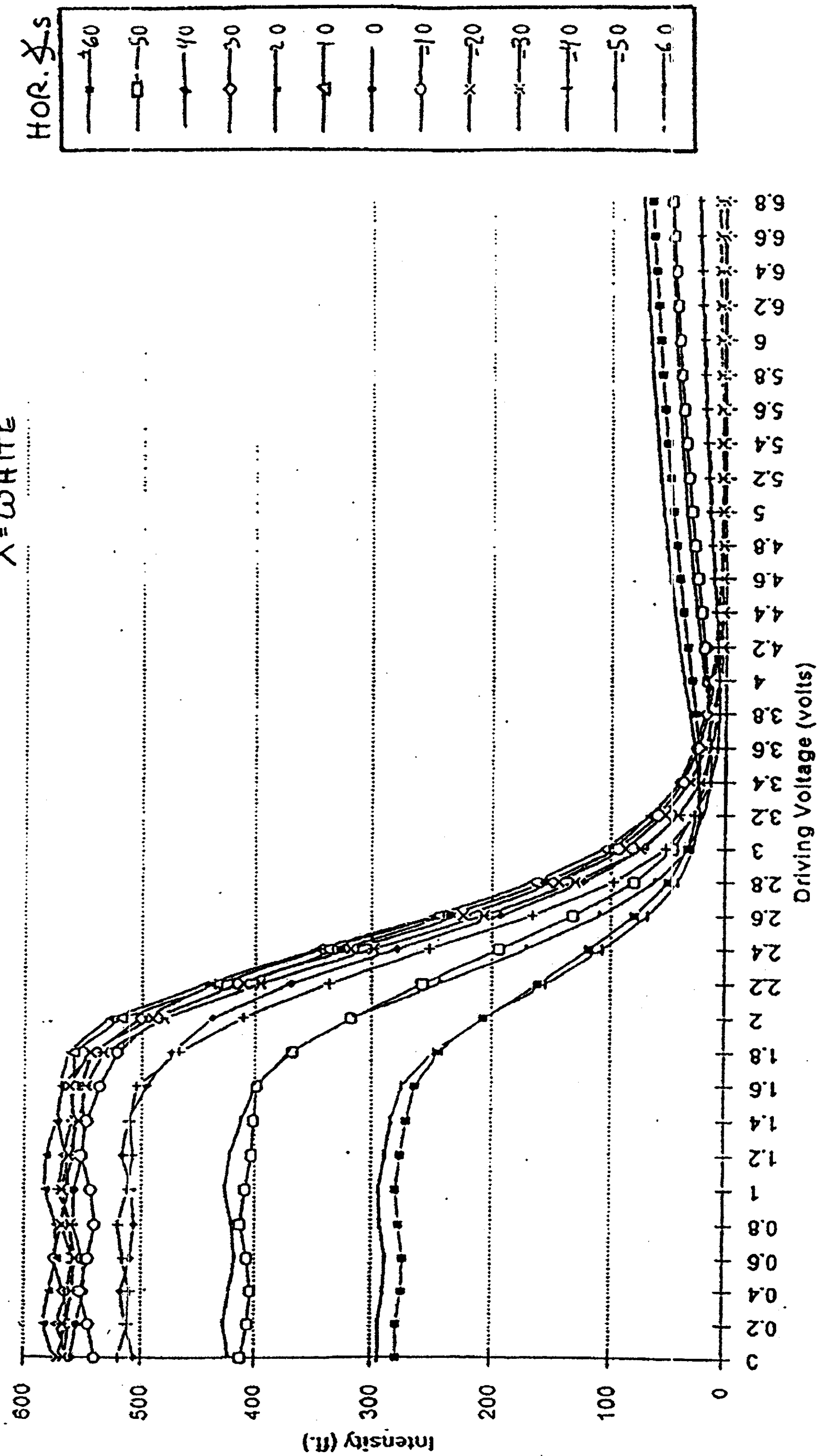


FIG. 31

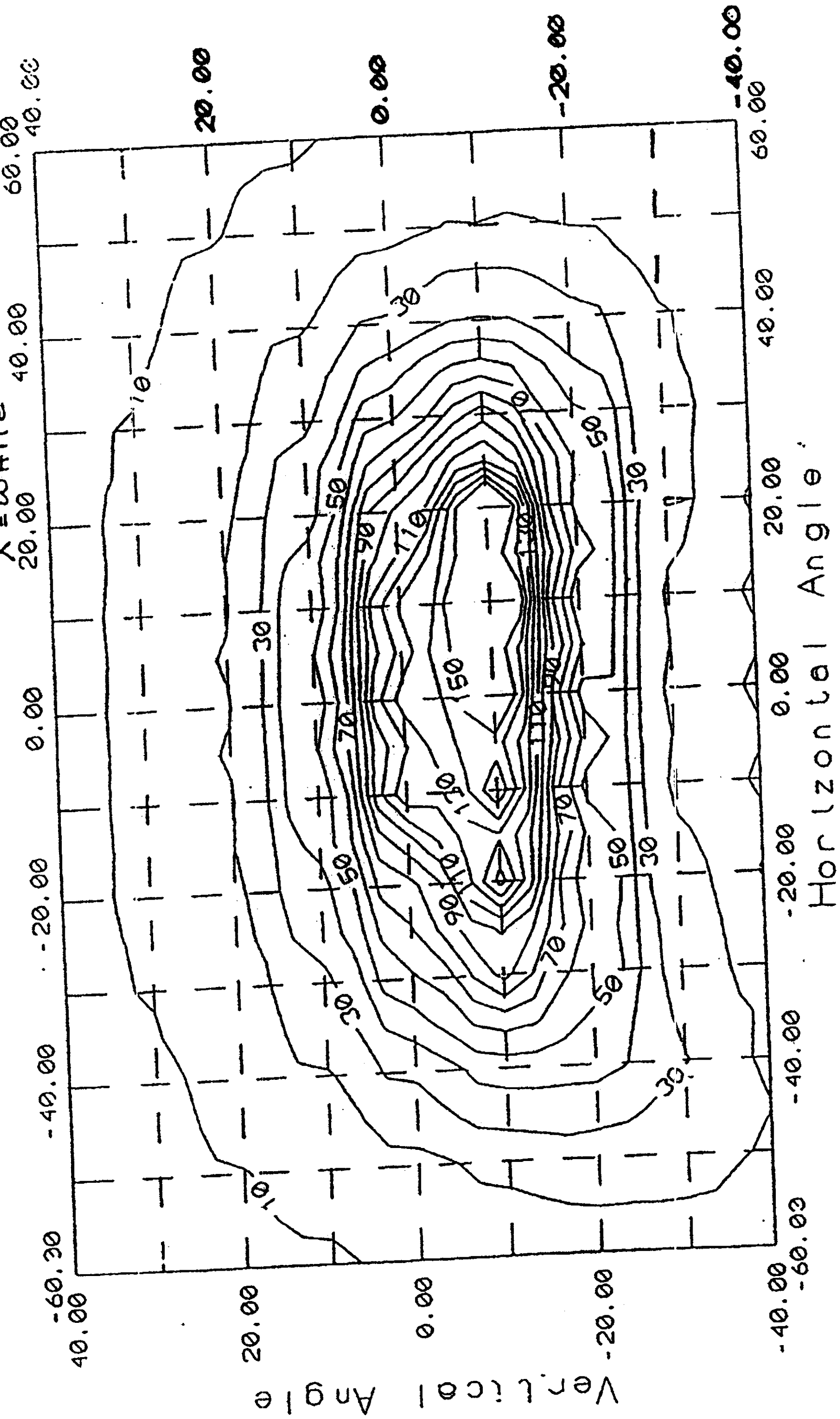
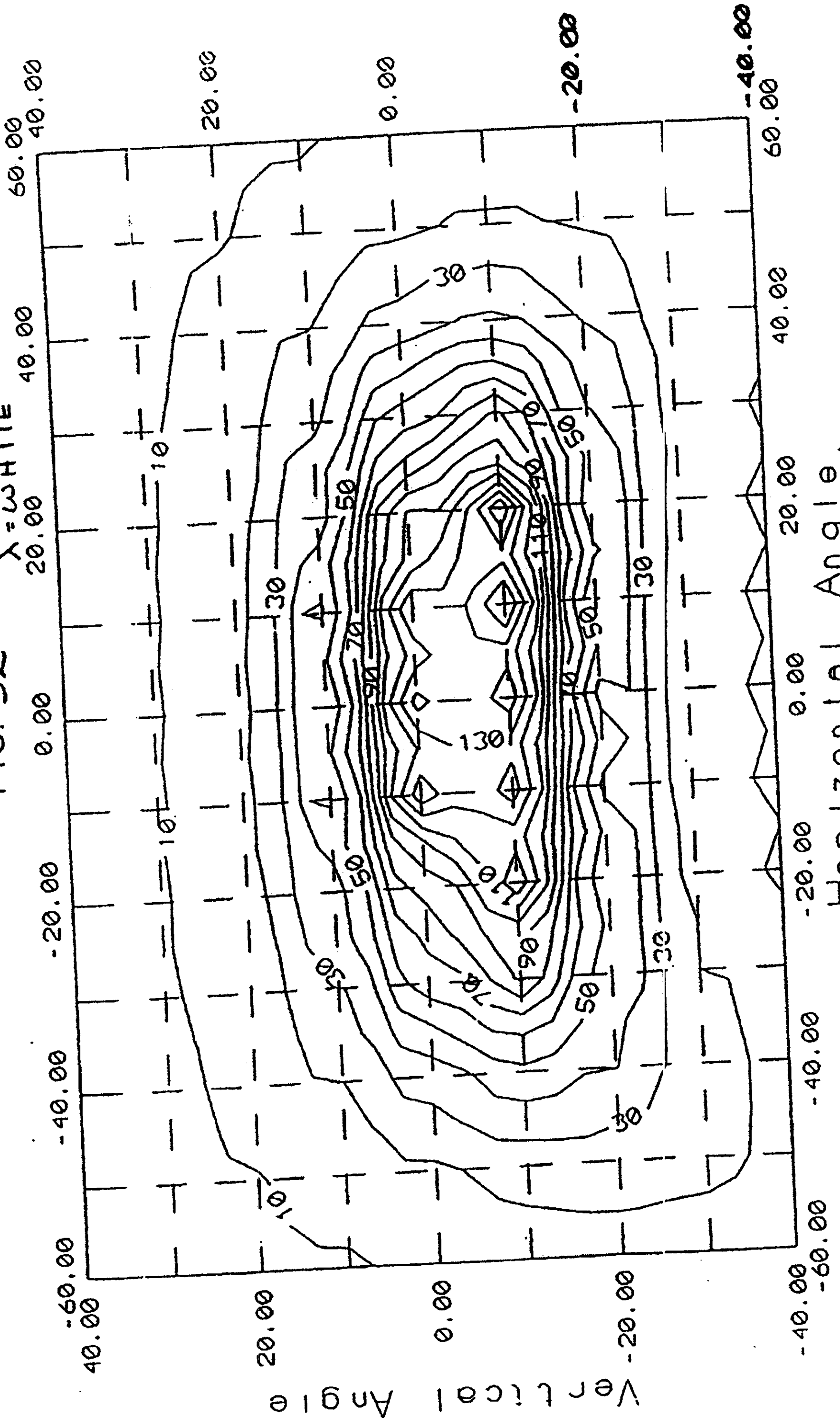


FIG. 32

V_{ON} = 6.0 V
R = 120nm
λ = WHITE



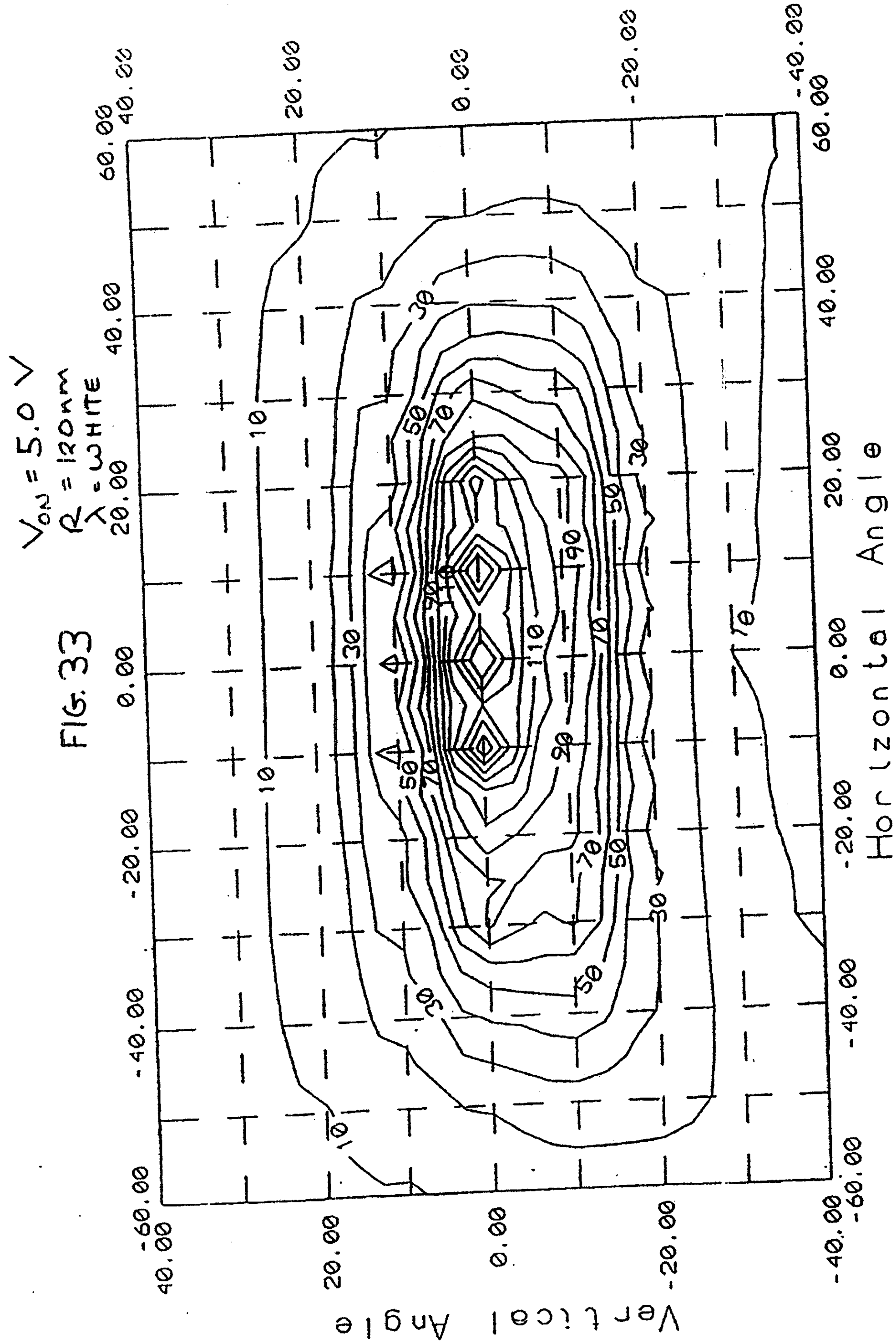


FIG. 33

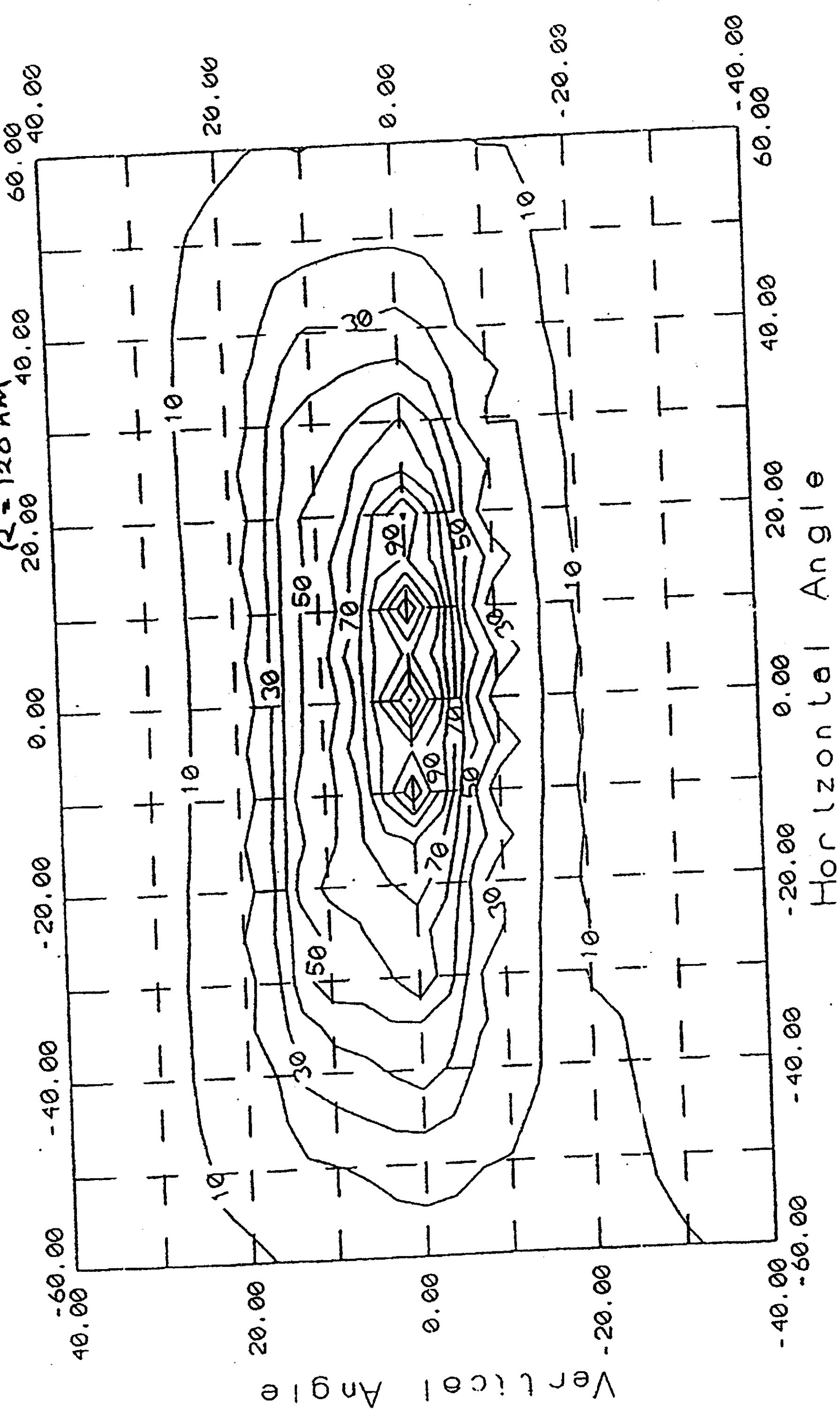

$V_{ON} = 4.0V$
λ = WHITE
R = 120 nm
Horizontal Angle
Vertical Angle
10
30
50
70
90
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00

FIG. 34

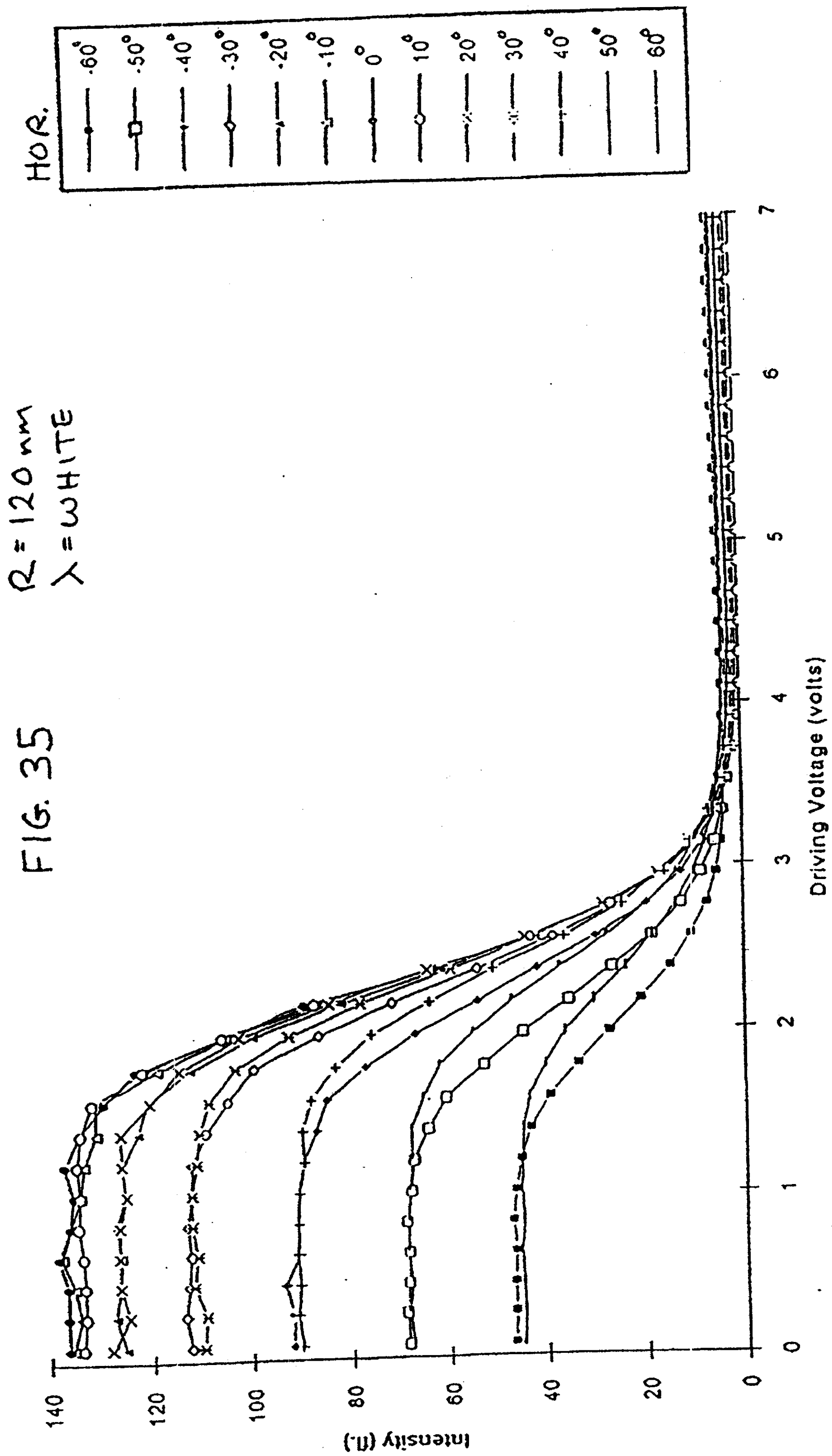

R = 120 nm
λ = WHITE
HOR.
-60°
-50°
-40°
-30°
-20°
-10°
0°
10°
20°
30°
40°
50°
60°
Intensity (fL)
140
120
100
80
60
40
20
0
Driving Voltage (volts)
0
1
2
3
4
5
6
7

FIG. 35

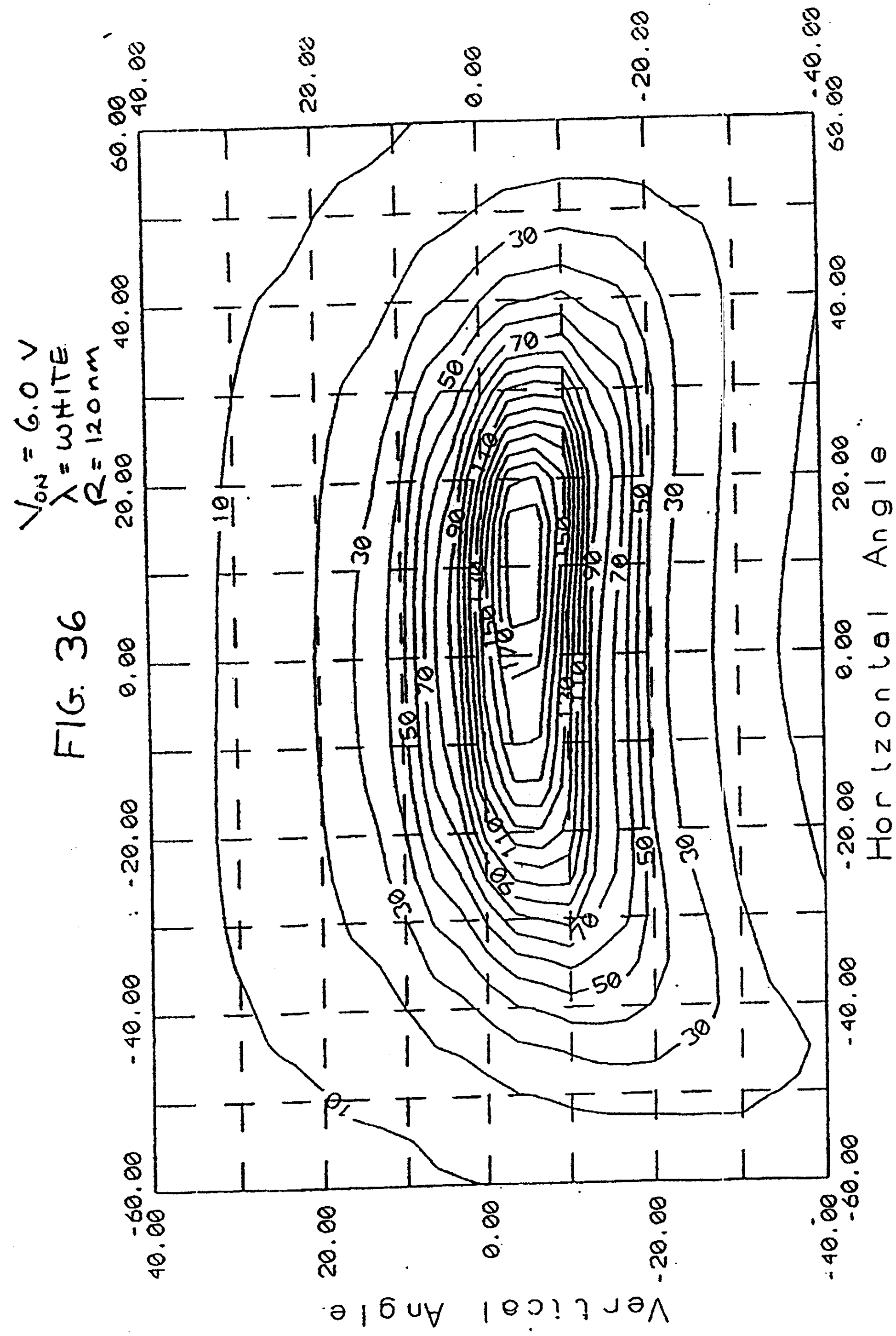
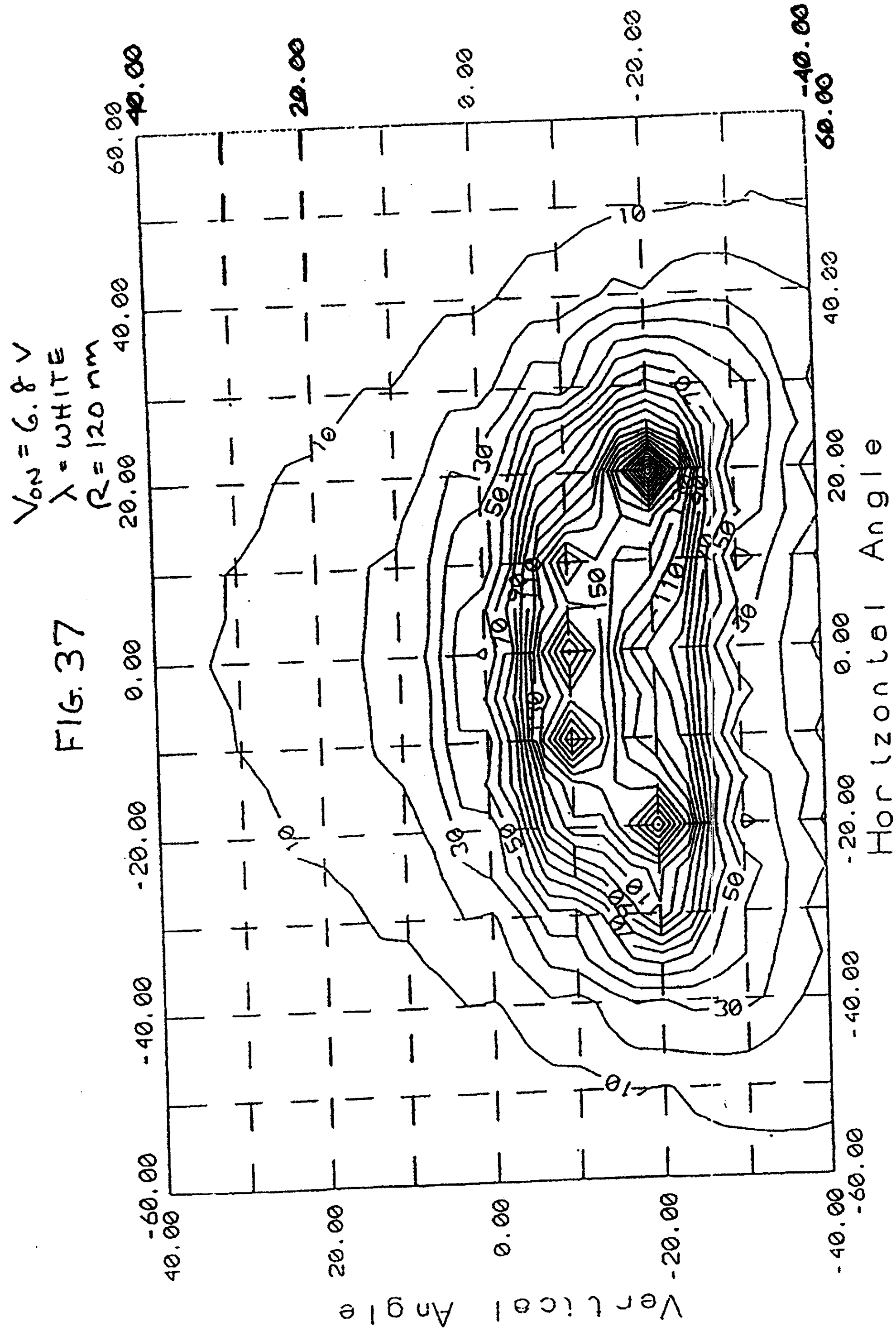


FIG. 36



$V_{ON} = 6.8$ V
λ = WHITE
R = 120 nm
Horizontal Angle
Vertical Angle

FIG. 37

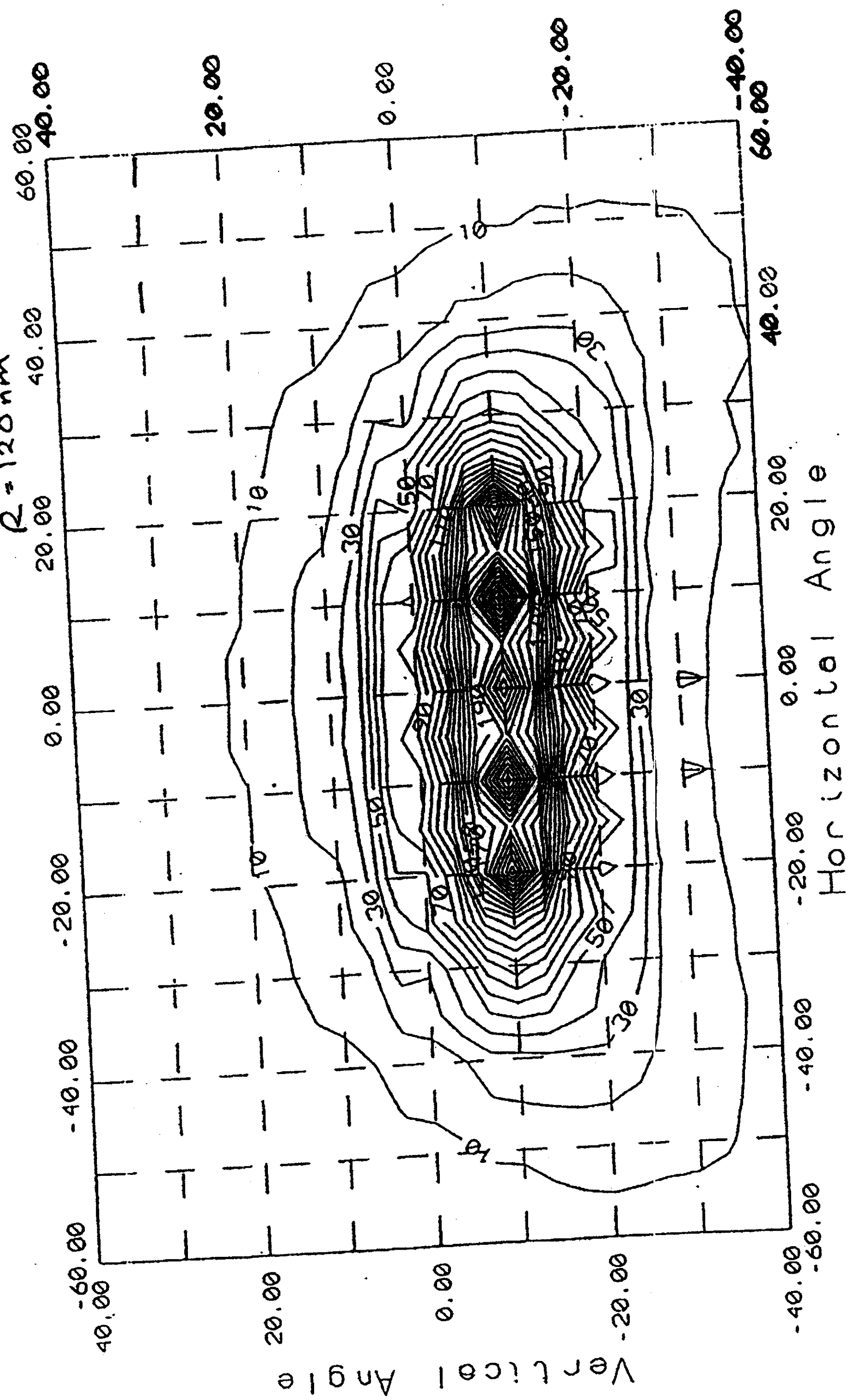
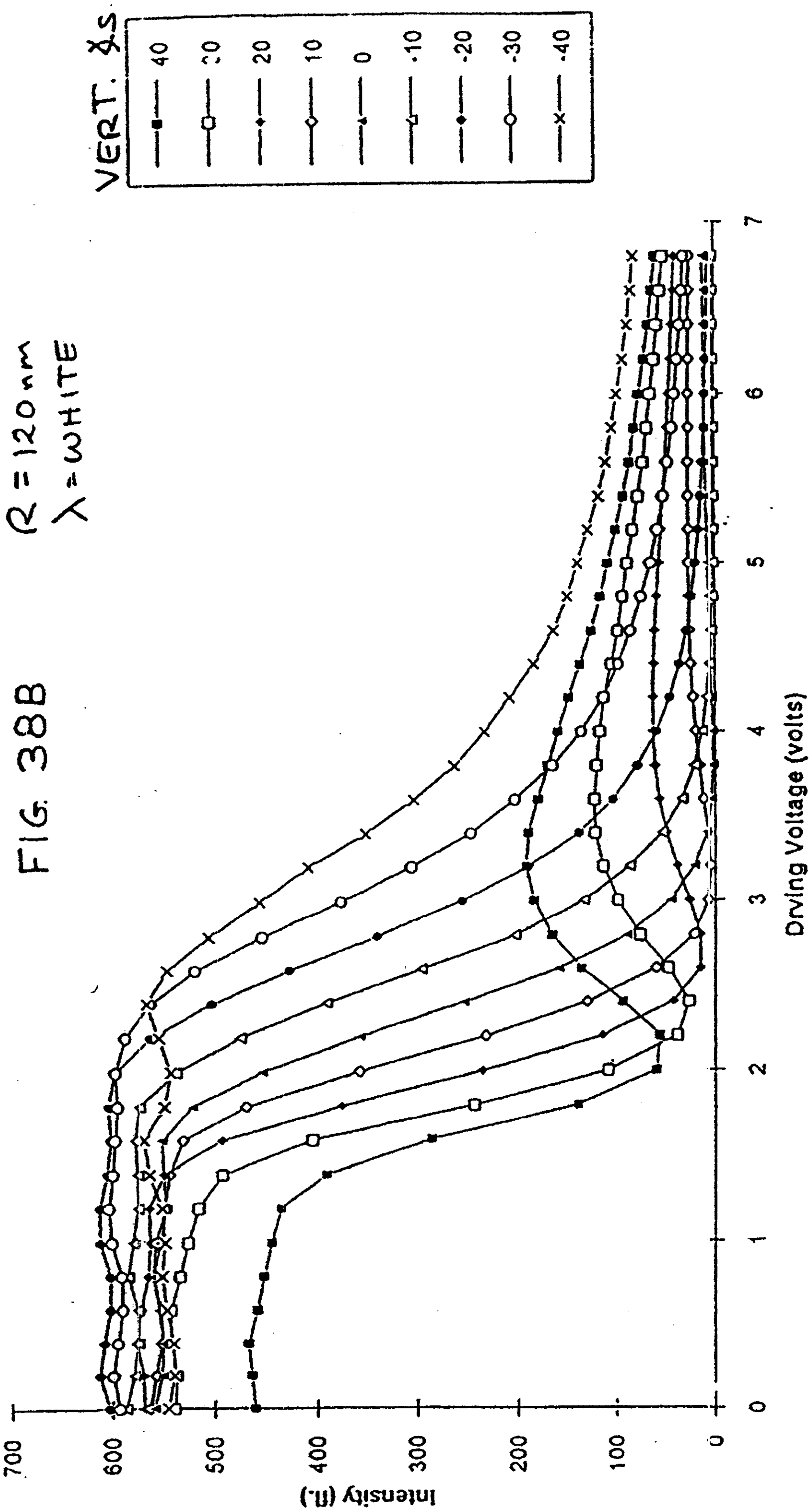


FIG. 38A

V_{ON} = 5.0 V
λ = WHITE
R = 120nm

FIG. 38B

R = 120nm
λ = WHITE



$V_{ON} = 6.0$ V
$R = 120$ nm
λ = WHITE

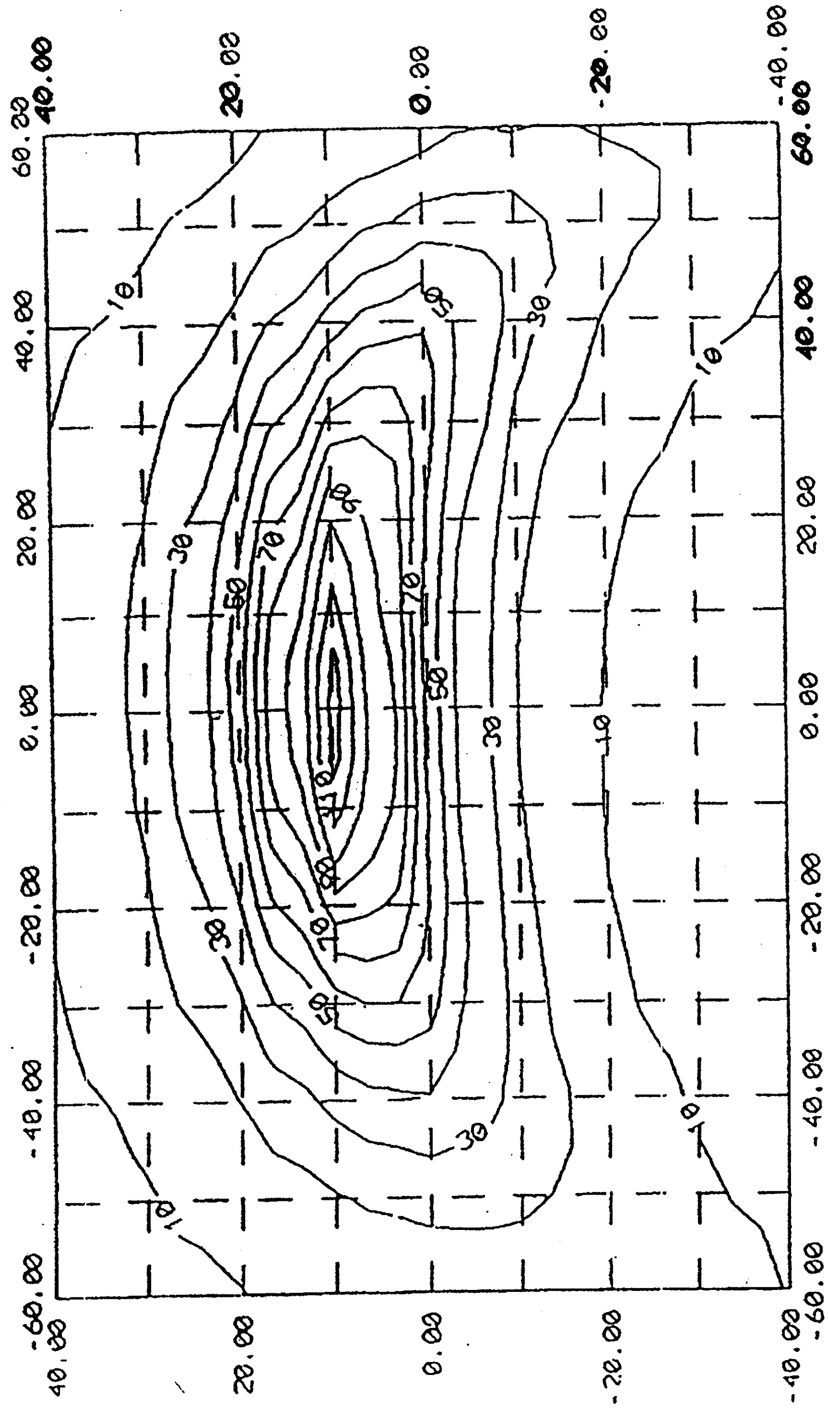


FIG. 39

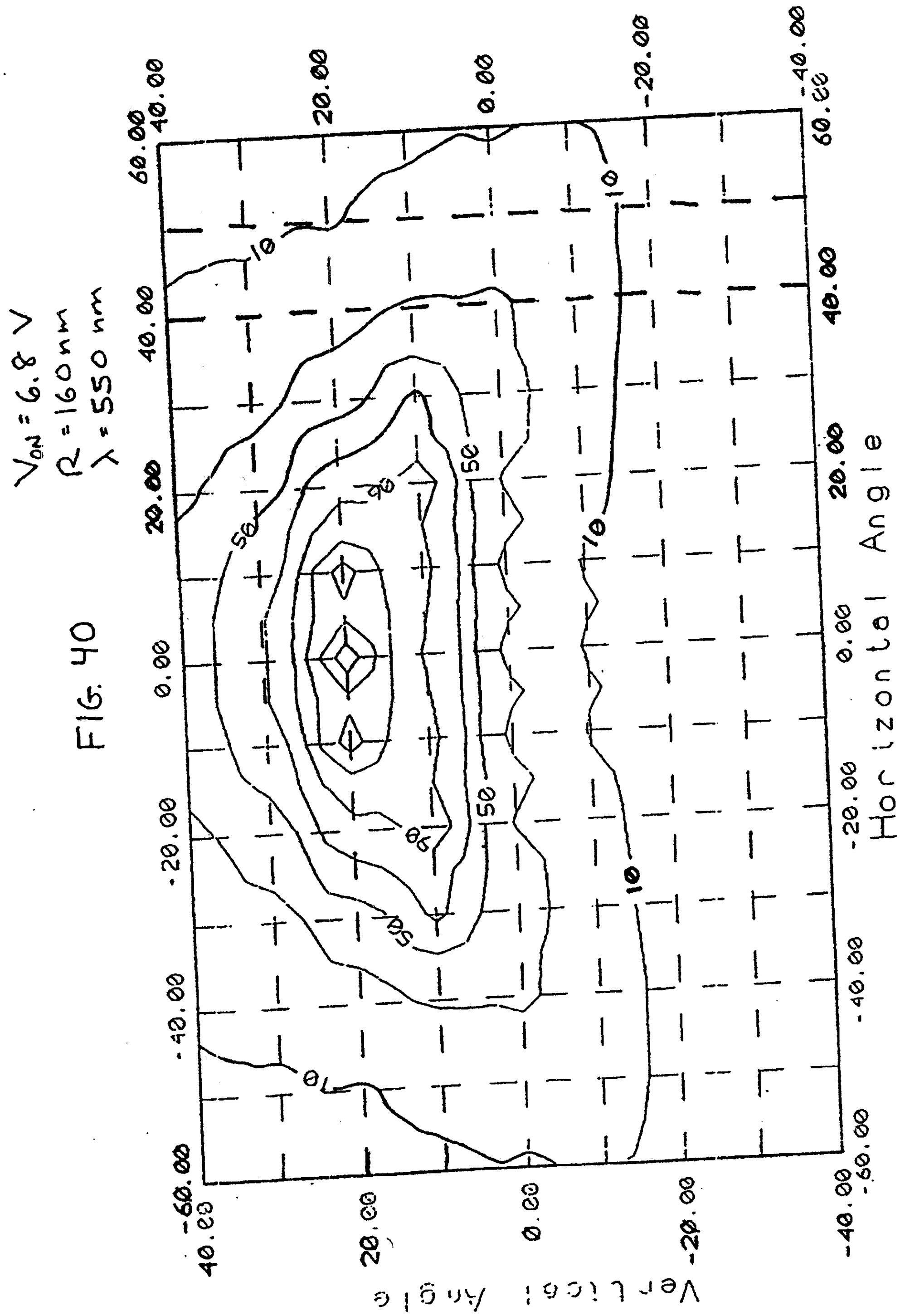

$V_{ON} = 6.8$ V
$R = 160$ nm
$\lambda = 550$ nm
10
50
90
Horizontal Angle
Vertical Angle
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00

FIG. 40

Fig. 42

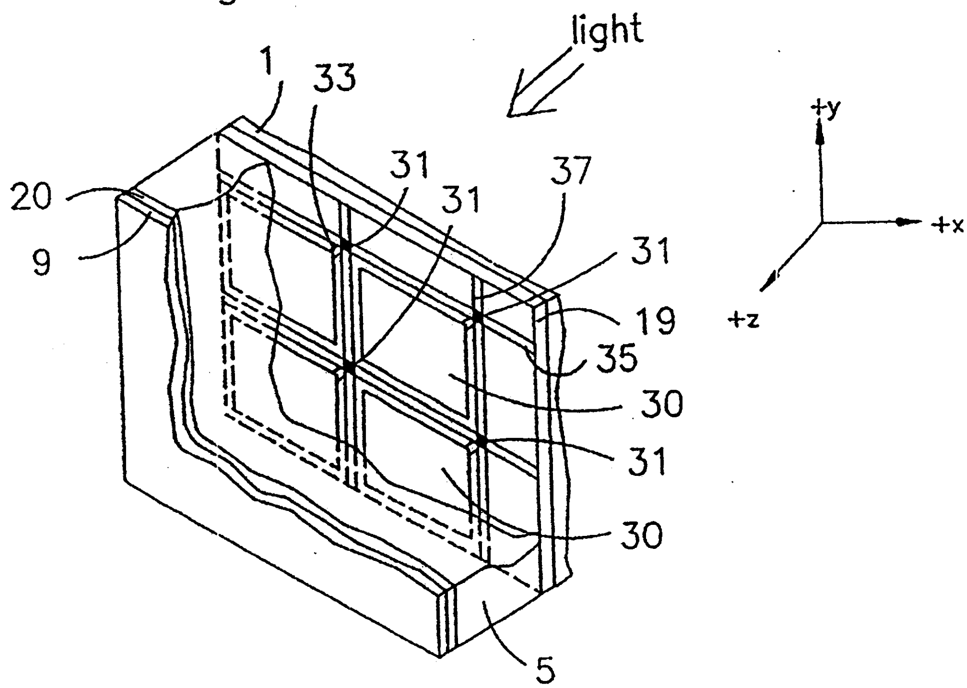
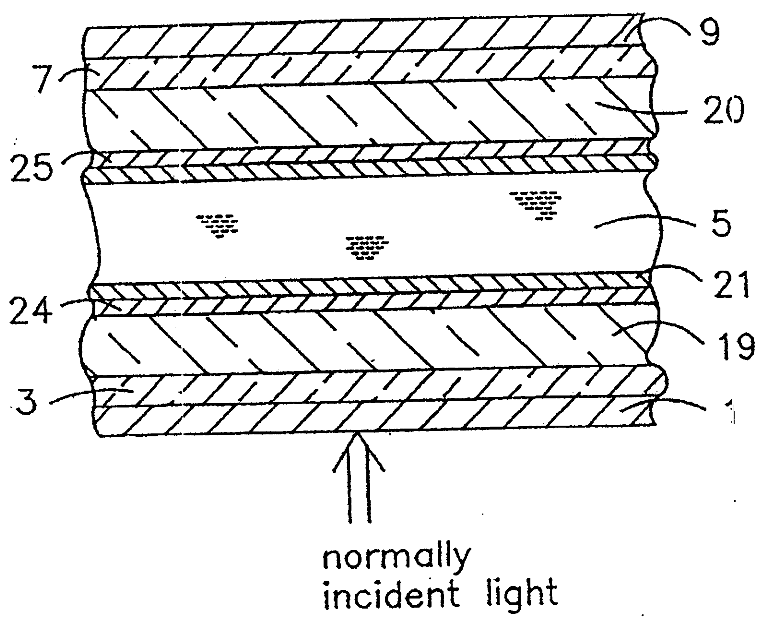

light
1
33
20
9
31
31
37
31
19
35
30
31
30
5
+y
+x
+z

Fig. 41


9
7
20
25
5
21
24
19
3
1
normally
incident light

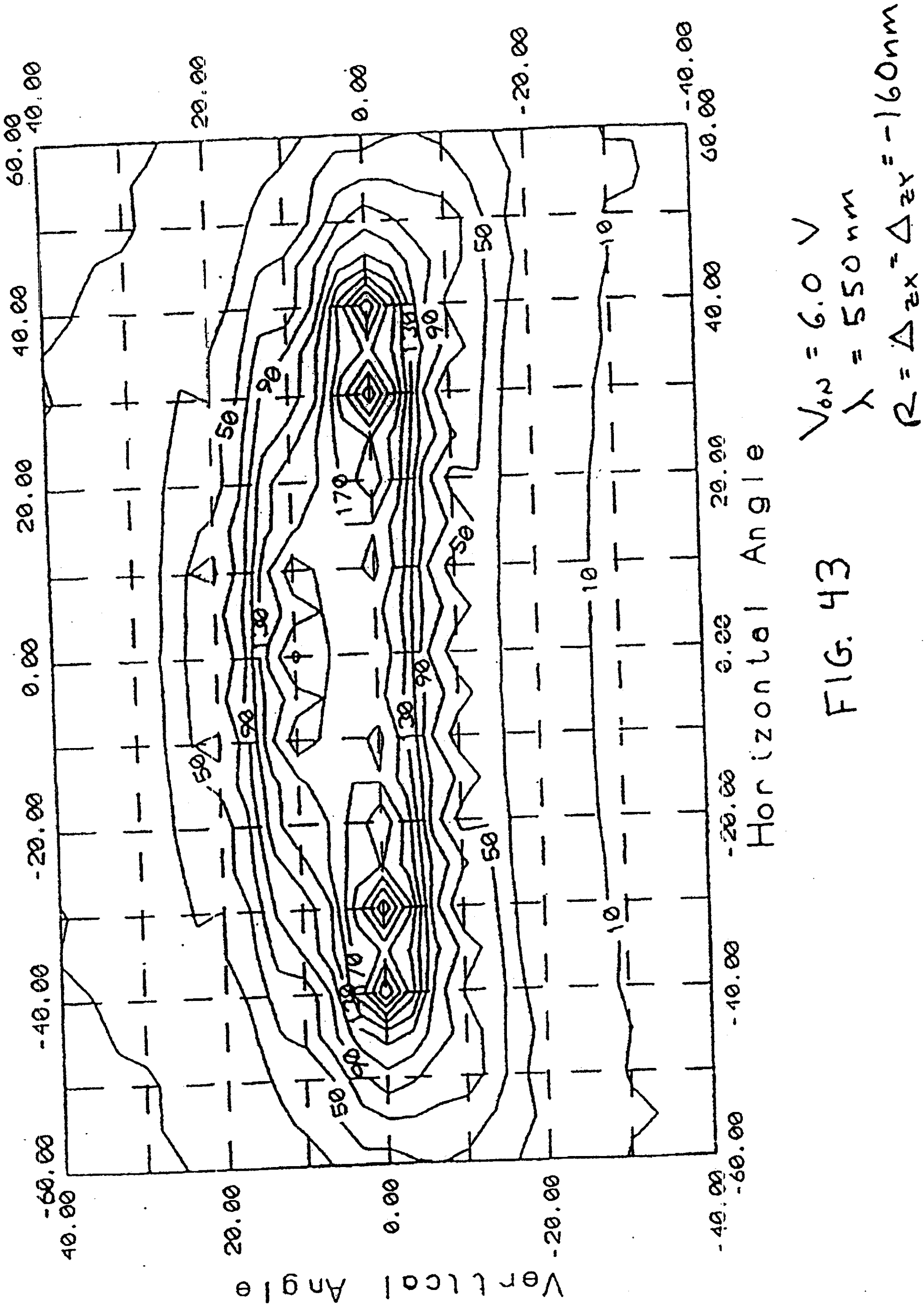

Horizontal Angle
Vertical Angle
$V_{on} = 6.0$ V
$\lambda = 550$ nm
$R = \Delta_{zx} = \Delta_{zy} = -160$ nm

FIG. 43

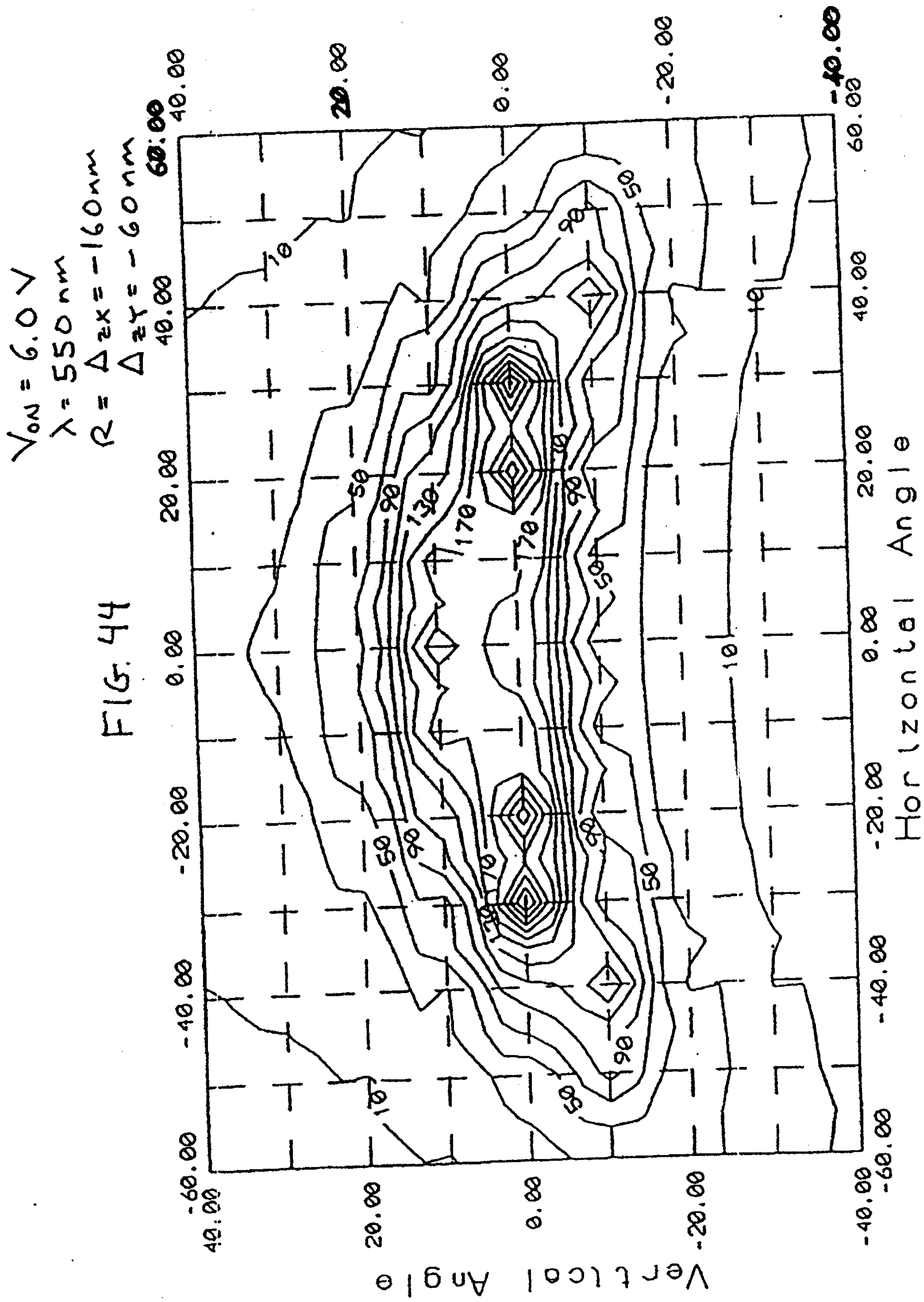
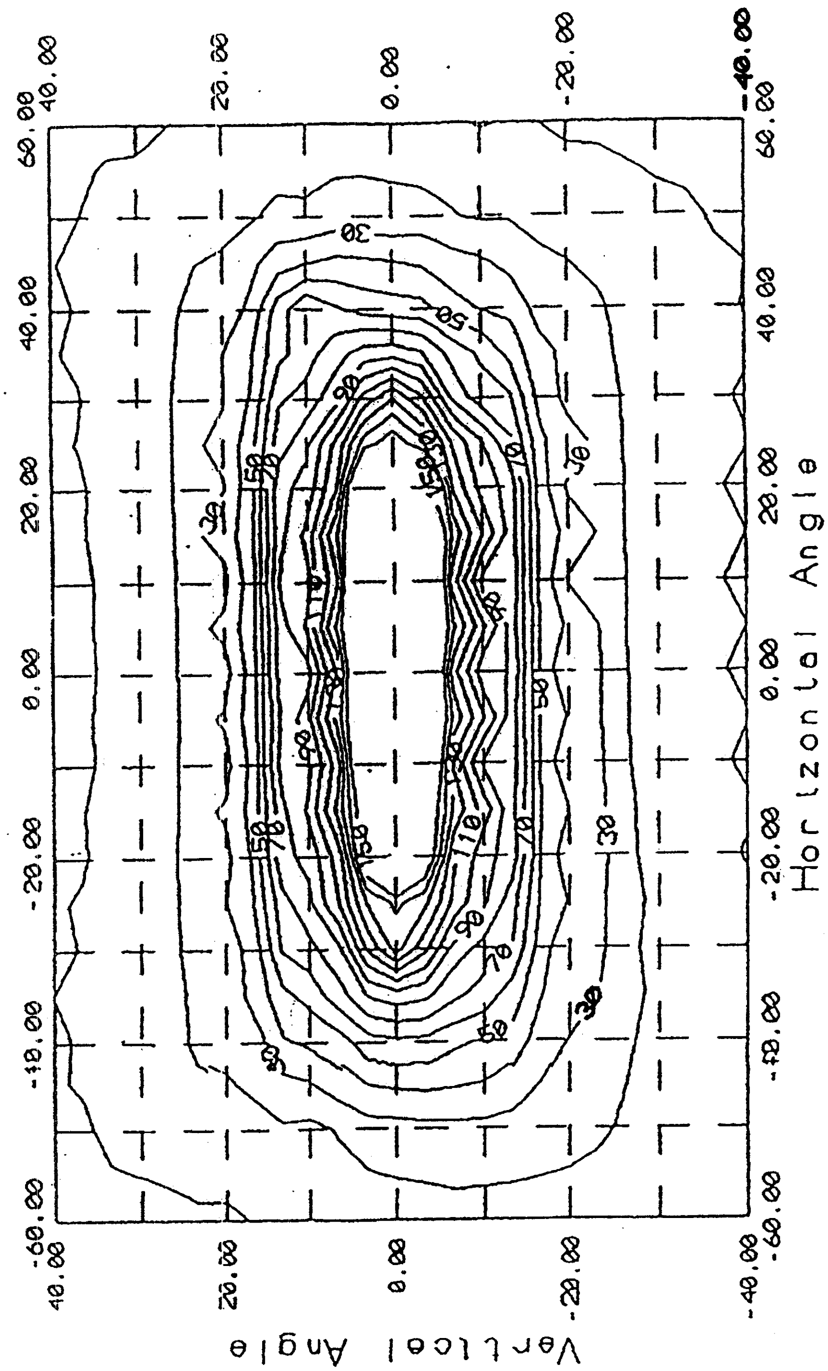

$V_{ON} = 6.0V$
$\lambda = 550nm$
$R = \Delta_{2X} = -160nm$
$\Delta_{2Y} = -60nm$
Horizontal Angle
Vertical Angle

FIG. 44



$V_{on} = 6.0$ V
λ = WHITE
R = BIAXIAL

FIG. 45

NORMALLY WHITE TWISTED NEMATIC LCD WITH RETARDATION FILMS ON OPPOSITE SIDES OF LIQUID CRYSTAL MATERIAL FOR IMPROVED VIEWING ZONE

This invention relates to a liquid crystal display having at least two retardation films, one on each side of a liquid crystal layer. More particularly, this invention relates to a normally white liquid crystal display which includes at least one retardation film having a retardation value of 80–200 nm on each side of the liquid crystal layer.

BACKGROUND OF THE INVENTION

Liquid crystal materials are useful for electronic displays because light traveling through a layer of liquid crystal (LC) material is affected by the anisotropic or birefringent value (ΔN) of the material, which in turn can be controlled by the application of a voltage across the liquid crystal material. Liquid crystal displays are desirable because the transmission or reflection of light from an external source, including ambient light and backlighting schemes, can be controlled with much less power than was required for the illuminance materials used in other previous displays. Liquid crystal displays (LCDs) are now commonly used in such applications as digital watches, calculators, portable computers, avionic cockpit displays, and many other types of electronic devices which utilize the liquid crystal display advantages of long-life and operation with low voltage and power consumption.

The information in many liquid crystal displays is presented in the form of a matrix array of rows and columns of numerals or characters, which are generated by a number of segmented electrodes arranged in such a matrix pattern. The segments are connected by individual leads to driving electronics, which apply a voltage to the appropriate combination of segments to thereby display the desired data and information by controlling the light transmitted through the liquid crystal material. Graphic information in, for example, avionic cockpit applications or television displays may be achieved by a matrix of pixels which are connected by an X-Y sequential addressing scheme between two sets of perpendicular conductor lines (i.e. row and column lines). More advanced addressing schemes use arrays of thin film transistors, diodes, MIMS, etc. which act as switches to control the drive voltage at the individual pixels. These schemes are applied predominantly to twisted nematic liquid crystal displays, but are also finding use in high performance versions of super twisted liquid crystal displays.

Contrast is one of the most important attributes determining the quality of both normally white (NW) and normally (NB) liquid crystal displays. Contrast, or the contrast ratio, is the difference between OFF state transmission versus ON state transmission. In normally black liquid crystal displays, the primary factor limiting the contrast achievable in these LCDs is the amount of light which leaks through the display in the darkened or OFF state. In normally white (NW) LCDs, the primary factor limiting the contrast is the amount of light which leaks through the display in the darkened or ON state. These problems are compounded in a bright environment, such as sunlight, where there is a considerable amount of reflected and scattered ambient light. In color liquid crystal displays, light leakage causes severe color shifts for both saturated and gray scale colors. These limitations are particularly important for avionic applications, where the copilot's viewing of the pilot's displays is important.

In addition, the legibility of the image generated by both normally black (NB) and normally white (NW) liquid crystal display devices depends on the viewing angle, especially in the matrix address device with a large number of scanning electrodes. Absent a retardation film, the contrast ratio of a typical NB or NW liquid crystal display is usually at a maximum only within a narrow viewing (or observing) angle centered about normal incidence (0° horizontal viewing angle and 0° vertical viewing angle) and drops off as the angle of view is increased.

It would be a significant improvement in the art to provide a liquid crystal display capable of presenting a high quality, high contrast image over a wide field of view.

Normally black liquid crystal displays are quite sensitive to cell gap, or the thickness "d" of the liquid crystal material, as well as to the temperature of the liquid crystal material. Therefore, normally black liquid crystal displays must be manufactured in accordance with rather specific tolerance parameters related to the cell gap of the display making them both difficult and expensive to make. One way in which to compensate for the normally black displays high sensitivity to cell gap is to provide such a multi-colored display with a multi-gap design wherein the thickness "d" of the liquid crystal material for each colored subpixel is matched to the first transmission minimum of the color of that subpixel. See, for example, U.S. Pat. No. 4,632,514 which utilizes the multi-gap approach by varying the liquid crystal material thickness "d" for the red, green, and blue subpixels therein so as to match the thickness "d" of each subpixel to the three different transmission minimums representative of the colors red, green, and blue. This increases, of course, the difficulty and expense of manufacturing this type of LCD.

Although a normally black display is rather sensitive to temperature and cell gap "d", a significant advantage associated with this type of liquid crystal display is that it provides good contrast ratios at wide viewing angles. Thus, a viewer may satisfactorily observe the data of the display throughout a wide range of viewing angles. Contrast ratio curves of, for example, 10:1 in normally black displays often extend up to viewing angles of, for example, 0° vertical, ±60° horizontal. The fact that normally black displays have such good contrast ratios at such large horizontal viewing angles enables them to be used in commercial applications where such viewing angles are required or preferred. Furthermore, NB displays generall experience more darkened state leakage than do NW displays at the normal viewing angle given current manufacturing technology.

Turning now to normally white liquid crystal displays, NW displays are fairly insensitive to the temperature and cell gap "d" of liquid crystal material. This allows for the manufacturing tolerances associated with the development of normally white displays to be lessened. Hence, normally white displays are easier and cheaper to manufacture than their normally black counterparts. However, while normally white LCDs are less sensitive to temperature and cell gap than normally black LCDs, their contrast ratios at large viewing angles are generally small relative to those of normally black displays. For example, 10:1 contrast ratio curves in normally white displays often only extend up to horizontal viewing angles of about 0° vertical, ±35° horizontal. This is significantly less than the extent to which the same contrast ratio curves extend horizontally in normally black displays. Therefore, while normally white LCDs are easier and cheaper to manufacturer than normally black

liquid crystal displays, they have a smaller range of satisfactory viewing angles than do normally black displays. It would satisfy a long felt need in the art if one could provide a NW display which had good contrast ratios at large viewing angles.

Several types of liquid crystal pixels or cells are in widespread use in flat panel displays. Active matrix addressing allows such displays to present a full color image with high resolution. When viewed directly at a normal or ON axis viewing angle (0° vertical, 0° horizontal viewing angle), a liquid crystal display of either the normally black or normally white type provides a generally high quality output, especially when the cell gap "d" is matched to the first transmission minimum, but the image degrades and contrast ratios decrease at increased viewing angles. This occurs because liquid crystal cells operate by virtue of the anisotropic or birefringent effect exhibited by their liquid crystal layer which includes a large number of anisotropic liquid crystal molecules. Such a material will be positively uniaxially birefringent (i.e., the extraordinary refractive index is larger than the ordinary refractive index). The phase retardation effect such a liquid crystal material has on light passing through it inherently varies or increases with the inclination angle of light, leading to lower contrast ratios and a lower quality image at larger viewing angles. By introducing an optical compensating element (or retarder) into the liquid crystal pixel or cell, however, it is possible to correct for the unwanted angular effects and thereby maintain higher contrast at both normal and larger viewing angles than otherwise possible.

The type and orientation of optical compensation or retardation required depends in part upon the type of display, normally black or normally white, which is used.

In a normally black (NB) twisted nematic display, the twisted nematic liquid crystal material is placed between polarizers whose transmission axes are parallel to one another. In the unenergized OFF state (no voltage above the threshold voltage V_{th} is applied across the liquid crystal material), normally incident light from the backlight is first polarized by the rear polarizer and in passing through the pixel or cell has its polarization direction rotated by the twist angle of the liquid crystal material dictated by the buffing zones. This effect is known as the twisting effect. The twist angle is set, for example, to be about 90° so that the light is blocked or absorbed by the front or output polarizer when the pixel is in the OFF state. When a voltage is applied via electrodes across the normally black pixel, the liquid crystal molecules are forced to more nearly align with the electric field, eliminating the twisted nematic optical effect of the LC material. In this orientation, the optical molecular axes of the liquid crystal layer molecules are perpendicular to the cell walls. The liquid crystal layer then appears isotropic to normally incident light, eliminating the twist effect such that the light polarization state is unchanged by propagation through the liquid crystal layer so that light can pass through the output polarizer. Patterns can be written in a normally black display by selectively applying a variable voltage to the portions of the display which are to appear illuminated.

Turning again to normally white (NW) LCD cells, in a normally white liquid crystal display configuration, a twisted nematic cell preferably having a twist angle of about 80°–100° (most preferably about 90°) is placed between polarizers which have substantially crossed or perpendicular transmission axes, such that the transmission axis of each polarizer is either parallel (P-buffed) or perpendicular (X-buffed) to the buffing direction or orientation of the liquid crystal molecules in the interface region of the liquid crystal material adjacent each polarizer. In other words, normally white cells can be either P-buffed where both polarizer axes are substantially parallel to their respective adjacent buffing zones, or X-buffed where both polarizer axes are substantially perpendicular to their respective adjacent buffing zones.

This NW orientation of the polarizers reverses the sense of light and dark from that of the normally black displays discussed above. The OFF or unenergized (no applied voltage above V_{th} across the liquid crystal material) areas appear light in a normally white display, while those which are energized appear dark.

The problem of ostensibly dark areas appearing light or colored when viewed at large angles still occurs, however, thereby creating the aforesaid lowered contrast ratios at reasonably large viewing angles. The reason for the reduced contrast ratios at large viewing angles in normally white displays is different than the reason for the problem in normally black displays. In the normally white energized darkened areas, the liquid crystal molecules tend to align with the applied electric field. If this alignment were perfect, all of the liquid crystal molecules in the cell would have their long axes normal to the glass substrate or cell wall. In the energized state, the normal white display appears isotropic to normally incident light, which is blocked by the crossed polarizers, thus, resulting in a darkened pixel or subpixel.

The loss of contrast with increased viewing angles in normally white pixels or displays occurs primarily because the homeotropic liquid crystal layer does not appear isotropic to OFF axis or OFF normal light. Light directed at OFF normal angles through the liquid crystal material propagates in two modes due to the anisotropy or birefringence (ΔN) of the liquid crystal layer, with a phase delay between these modes which increases with the incident angle of light. This phase dependence on the incident angle introduces an ellipticity to the polarization state which is then incompletely extinguished by the front or exit polarizer in the normally white cell, giving rise to light leakage. Because of the normally white symmetry the birefringence has no azimuthal dependence.

Accordingly, what is needed in normally white displays is an optical compensating or retarding element which introduces a phase delay that restores the original polarization state of the light, allowing the light to be blocked by the output polarizer in the ON state. Optical compensating elements or retarders for normally white displays are known in the art and are disclosed, for example, in U.S. Pat. Nos. 5,184,236; 5,196,953; 5,138,474; and 5,071,997, the disclosures of which are hereby incorporated herein by reference. It is known that the polyimides and copolyimides disclosed by aforesaid U.S. Pat. No. 5,071,997 can be used as negative birefringent retarding elements in normally white liquid crystal displays and are said to be custom tailorable to the desired negative birefringent values without the use of stretching. The polyimide retardation films of U.S. Pat. No. 5,071,997 are uniaxial but with an optical axis oriented in the Z direction which is perpendicular to the plane defined by the film.

Quite often, the retardation films or plates used in conjunction with normally white displays have a negative birefringent value. However, in certain cases, retardation films having a positive birefringent value are used in combination with such normally white cells. An example of this is U.S. Pat. No. 5,184,236 which will be discussed more fully below.

FIG. 1 is a contrast ratio curve graph for a prior art normally white light valve pixel. The light valve for which

the contrast ratio curves are illustrated in FIG. 1 includes a rear polarizer having a transmission axis defining a first direction, a front or exit polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another, a liquid crystal material having a cell gap "d" of 5.86 μm, a rear buffing zone oriented in the second direction, and a front buffing zone orientated in the first direction. The temperature was 34.4° C. when the graph illustrated by FIG. 1 was plotted. This light valve pixel did not include a retarder. The above-listed parameters with respect to FIG. 1 are also applicable to FIGS. 2 and 3.

The contrast ratio graph of FIG. 1 was plotted utilizing a 6.8 V driving voltage V_{ON}, and a 0.2 volt V_{OFF}. As can be seen in FIG. 1, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis only to angles of about −40° horizontal and +38° horizontal. Likewise, the 30:1 contrast ratio curve extends along the 0° vertical viewing axis only to horizontal angles of about ±30°. This graph is illustrative of the problems associated with normally white liquid crystal displays in that their contrast ratios at large horizontal and vertical viewing angles are fairly low.

FIG. 2 is a contrast ratio curve graph for the normally white light valve described above with respect to FIG. 1. However, the FIG. 2 graph was plotted utilizing a V_{ON} of 5.0 volts and a V_{OFF} of 0.2 volts. Again, the temperature was 34.4° C. As can be seen by comparing the graphs of FIG. 1 and FIG. 2, as the voltage applied to the liquid crystal material decreases, as in FIG. 2, the contrast ratio curves expand horizontally and contract vertically. The 10:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends a total of about 85° as opposed to only 78° in FIG. 1. Also, the 30:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends horizontally about 67° as opposed to only about 58° in FIG. 1. With respect to vertical viewing angles, the contrast ratio curves of 10:1 and 30:1 in FIG. 2 do not extend along the 0° horizontal viewing axis to the negative vertical extent that they did in FIG. 1. Accordingly, while the normally white light valve of FIGS. 1–3 has less than desirable contrast ratios at large viewing angles, the contrast ratios expand horizontally and contract vertically as the voltage across the liquid crystal material decreases.

FIG. 3 is a driving voltage versus intensity plot for the light valve pixel described above with respect to FIGS. 1–2 illustrating the gray level characteristics of the pixel. The various curves represent horizontal viewing angles from −60° to +60° along the 0° vertical viewing axis.

Gray level performance of a liquid crystal display is very important. Conventional liquid crystal displays utilize anywhere from about eight to sixty-four different driving voltages. The different driving voltages are referred to as "gray level" voltages. The intensity of the light transmitted through the pixel or display depends upon the driving voltage. Accordingly, gray level voltages are used to generate different shades of different colors and to create different colors when these shades are mixed with one another. Preferably, the higher the driving voltage in a NW display, the lower the intensity of light transmitted therethrough. Likewise then, the lower the driving voltage, the higher the intensity of light emitted from the preferred forms of a normally white display. The opposite is true in a normally black display. Thus, by utilizing multiple gray level driving voltages, one can manipulate either an NW or NB liquid crystal display pixel to emit a desired intensity of light. A gray level V_{ON} is any voltage greater than V_{th} up to about 5.0–6.5 V.

Gray level intensity performance for LCDs is dependent upon the displays' driving voltage. It is desirable in gray

level performance of NW displays to have an intensity versus driving voltage curve wherein the intensity of the light emitted from the pixel continually and monotonically decreases as the driving voltage increases. In other words, it is desirable to have gray level performance in a pixel such that the intensity at 6.0 volts is less than that at 5.0 volts, which is in turn less than that at 4.0 volts, which is less than that at 3.0 volts, which is in turn less than that at 2.0 volts, etc. Such good gray level curves across wide ranges of viewing angles allow the intensity of radiation emitted from the pixel to be easily controlled.

Turning again now to FIG. 3, the intensity versus driving voltage curves illustrated therein with respect to the prior art light valve pixel of FIGS. 1–2 having no retardation film are undesirable because of the inversion hump present in the area of the curves having voltages greater than about 3.2 volts. The term "inversion hump" means that the intensity aspect of the curve monotonically decreases as the driving voltage increases in the range of about 1.6–3.0 volts, but at a driving voltage of about 3.2 volts, the intensities at a plurality of viewing angles begin to rise as the voltage increases from about 3.2 volts to 6.8 volts. This rise in intensity as the voltage increases is known as an "inversion hump." The inversion hump of FIG. 3 includes only a rise portion. However, such inversion humps often include both a rise and fall portion. The presence of this inversion hump with respect to a plurality of horizontal viewing angles as shown in FIG. 3 means that as gray level voltages between, for example, 1.6 and 3.0 volts increase, the intensity of radiation emitted from the pixel decreases accordingly. However, as gray level voltages above 3.0 volts increase from 3.2 volts all the way up to 6.8 volts, the intensity of radiation emitted from the pixel increases. This is undesirable. A perfect driving voltage versus intensity curve would have a decreased intensity for each increase in gray level driving voltage. In contrast to this, the inversion hump represents an increase in intensity of radiation emitted from the light valve pixel for each increase in gray level driving voltage above about 3.2 volts for certain viewing angles. Accordingly, it would satisfy a long felt need in the art if a liquid crystal display and pixels therein could be provided with no or little inversion. In other words, the smaller the rise in intensity for an increase in driving voltage at all gray levels, the better.

FIG. 4 is a schematic illustration showing an optical arrangement of a normally white liquid crystal display device disclosed in U.S. Pat. No. 5,184,236. As illustrated, the LCD includes a rear polarizer **111**, a rear retardation plate or film **113**, a liquid crystal cell **119** including a liquid crystal material sandwiched between a rear orientation or buffing zone oriented in direction A_0 and a front orientation or buffing zone oriented in direction A1, a front retardation film **114**, and finally a front polarizer **112**.

The rear polarizer **111** is provided at the light incident side of the liquid crystal layer **119**, a front or exit polarizer **112** is provided at the light exit side of the liquid crystal layer **119**, a rear retardation film **113** is provided between the liquid crystal layer and the polarizer **111**, and a front retardation film **114** is provided between the liquid crystal layer and the front polarizer **112**. This prior art NW display is "P-buffed" because the rear polarizer transmission axis P_1 is parallel to the rear orientation direction A_0, and the front polarizer transmission axis P_2 is parallel to the front orientation direction A_1.

The product of parameters "ΔN·d" of the liquid crystal layer **119** is set in the range of 450–550 nm. The liquid crystal material of U.S. Pat. No. 5,184,236 is left handed as

defined in the art. The aligning direction of the rear orientation film on the light incident side of the liquid crystal layer **109** is a rubbing direction A_0 inclined at approximately 45° with respect to the side of the liquid crystal cell. The aligning direction of the orientation or buffing film on the front side of the liquid crystal layer is oriented in direction A_1 which is rotated about 90° in a counterclockwise direction from the orientation direction A_0 of the orientation film on the rear side of the liquid crystal material. Therefore, the liquid crystal layer **119** sandwiched between the opposing orientation films is twisted substantially 90°. The pretilting angle of the liquid crystal molecules is approximately 1°.

The rear linear polarizer **111** has a transmission axis P_1 which is parallel to the orientation direction A_0, while the front polarizer **112** has a transmission axis direction P_2 which is parallel to the front orientation direction A_1. The transmission axes of the front and rear polarizers **112** and **111** are perpendicular to one another thereby defining a normally white liquid crystal display. The rear retardation plate or film **113** is so arranged that its optical axis R_1 is either parallel to or crosses at 90° to the rear rubbing direction A_0. The front retardation film **114** is so arranged that its optical axis R_2 is either parallel to or crosses at 90° to the rubbing direction A_1. These retardation films **113** and **114** are formed to have equal retardation values ($d \cdot \Delta N$) where "d" is the thickness of the retardation film and "ΔN" is the anisotropic or birefringent value of the retardation film. The retardation values of the retardation films **113** and **114** are set in the range of 300–400 nm. The front and rear retardation films are formed of the same material such as, for example, a polycarbonate or polyvinyl alcohol, and the outer surfaces thereof are preferably covered with a protective film made of triacetyl cellulose or the like.

The orientation or buffing directions of prior art FIG. 4 are "six o'clock buffed." The term "six o'clock buffed" means that the rear and front orientation directions A_0 and A_1 are oriented in directions so as to provide a viewing zone having an extended region in the six o'clock area of the graphs shown in FIGS. 5A–5D. In other words, because the orientation direction A_0 goes from the upper left to the lower right as shown in FIG. 4, and orientation direction A_1 goes from lower left to upper right, the resulting viewing zone has better contrast as shown in FIGS. 5A–5D in the negative vertical region below the 0° vertical viewing axis. This is what is meant by the phrase "six o'clock buffed."

Alternatively, if the orientation direction A_0 went from the lower right to the upper left, and the orientation direction A_1 was directed from the upper right to the lower left, then the display of FIG. 4 would have been "twelve o'clock buffed" and would have provided a viewing zone having better contrast ratios in the positive vertical viewing angles instead of the negative vertical viewing angles. The six o'clock buffed LCDs of FIGS. 4 and 5A–5D illustrate viewing zones with better contrast ratios in the negative vertical area below the 0° vertical viewing axis as opposed to the positive vertical viewing area above the 0° vertical viewing axis.

In the prior art liquid crystal display of FIG. 4, the contrast ratios are measured in FIGS. 5A–5D for the four possible cases of retardation film orientation, when the value of $d \cdot \Delta N$ of a liquid crystal layer **119** is set to 510 nm and the retardation value of both retardation films **113** and **114** is set to 350 nm (the value measured by the light having a wavelength of 589 nm). The four cases are as follows.

FIG. 5A shows contrast ratio curves for the case where the optical axes of the rear and front retardation films **113** and **114** are disposed together in parallel to the rear rubbing direction A_0. The solid or outer contrast ratio curve in FIGS. 5A–5D represents a contrast ratio of 10:1. The inner or equally broken contrast curve in FIGS. 5A–5D represents a contrast ratio of 100:1. The intermediate contrast ratio curve in FIGS. 5A–5D represents a contrast ratio of 50:1. Furthermore, in the graphs of FIGS. 5A–5D, each circle represents a 10° shift in viewing angle. In other words, the center of the graph represents a 0° vertical and 0° horizontal viewing angle, the first circle represents 10°, the second circle 20°, etc. As can be seen in FIG. 5A, the 10:1 contrast ratio curve extends horizontally along the vertical 0° viewing axis to about −37° and +40°, and extends upwardly along the 0° horizontal viewing axis to about 15° vertical.

FIG. 5B shows contrast ratio curves for the case where the optical axis R_1 of the rear retardation film **113** is disposed in parallel to the orientation direction A_0, and the optical axis R_2 of the front retardation film **114** is disposed perpendicular to the rubbing direction A_0. The direction R_1 is parallel to the rear polarizer axis P_1, and R_2 is parallel to the front polarizer axis P_2. As can be seen in FIG. 5B, the 10:1 contrast ratio curve extends along the 0° horizontal viewing axis only to about 15° vertical. Also, the 50:1 contrast ratio curve extends along the 0° horizontal viewing axis only to about 5° vertical.

FIG. 5C shows contrast ratio curves for the case where the optical axes of the rear and front retardation films **113** and **114** are arranged in parallel with one another and cross at 90° to the rear buffing direction A_0. In FIG. 5C, the 10:1 contrast ratio curve extends upward along the 0° horizontal viewing axis only to about 15° vertical. Also, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis a total of about 75°–80°.

FIG. 5D shows contrast ratio curves for the case where the optical axis R_1 of the rear retardation film **113** is arranged to cross at 90° to the rubbing direction A_0, and the optical axis R_2 of the front retardation film **114** is arranged in parallel to rear orientation direction A_0. In FIG. 5D, the 10:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis a total of about 60°–65°. Also, the 10:1 contrast ratio curve in FIG. 5D extends upward along the 0° horizontal viewing axis only to about +15° vertical.

It was known prior to our invention to rotate retardation films to adjust the viewing zones of LCDs. For example, U.S. Pat. No. 5,184,236 teaches rotating the optical axes of retardation films ±15° or less when two such films are disposed on a single side of the liquid crystal material. The axes of the retardation films are rotated either in the clockwise or counterclockwise direction for the purpose of adjusting the viewing zone. However, when the retardation films of this patent are rotated, the symmetry of the viewing zone is substantially distorted thereby creating viewing zones which are not substantially symmetrical about the 0° horizontal viewing axis. Furthermore, this patent does not teach rotating one or both optical axes of rear and front retardation films ±15° or less for the purpose of adjusting the location of the display's viewing zone when the display includes rear and front retardation films with a liquid crystal layer therebetween.

FIG. 6 illustrates the angular relationships between the horizontal and vertical viewing axes and angles described herein relative to a liquid crystal display and conventional LCD angles ϕ and Θ. The +X, +Y, and +Z axes shown in FIG. 6 are also defined in other figures herein. Furthermore, the "horizontal viewing angles" (or X_{ANG}) and "vertical viewing angles" (or Y_{ANG}) illustrated and described herein may be transformed to conventional LCD angles ϕ and Θ by the following equations:

$$TAN(X_{ANG})=COS(\phi)\cdot TAN(\Theta)$$

$$SIN(Y_{ANG})=SIN(\Theta)\cdot SIN(\phi)$$

or

$$COS(\Theta)=COS(Y_{ANG})\cdot COS(X_{ANG})$$

$$TAN(\phi)=TAN(Y_{ANG})\div SIN(X_{ANG})$$

FIGS. 7–10 are computer simulation contrast ratio curve graphs of a normally white liquid crystal display having a cell gap "d" of 5.70 μm. The display includes a rear polarizer having a transmission axes defining a first direction, a rear retardation film having an optical axis parallel to the first direction, a rear buffing zone oriented perpendicular to the first direction, a front buffing zone parallel to the first direction, a front retardation film having an optical axis perpendicular to the first direction, and a front or exit polarizer having a transmission axis perpendicular to the first direction. The retardation films are of the positively birefringent uniaxial type. This LCD of FIGS. 7–10 is not prior art to this invention but is included in this section for the purpose of later comparison with certain embodiments of this invention.

FIG. 7 is a computer simulation contrast ratio graph of the aforesaid normally white liquid crystal display wherein the wavelength of light utilized was red at 630 nm, V_{ON} was 6.8 volts, and V_{OFF} was 0.9 volts. The retardation value of both the front and rear retardation films of the display simulated in FIGS. 7–10 was 320 nm. As can be seen in FIG. 7, the 10:1 contrast ratio curve extends along the 0° vertical viewing angle from horizontal angles of about −40° to +40° thereby defining along the 0° vertical viewing axis a 10:1 total viewing zone of about 80°.

FIG. 8 is a computer simulation graph of the aforesaid display also simulated by FIG. 7. The difference between the graph of FIG. 8 and the graph of FIG. 7 is that a 5.0 V_{ON} was used as a parameter in FIG. 8. As can be seen, a reduction in V_{ON} results in a shifting upward of the viewing zone to a position centered substantially above the 0° vertical viewing axis. Also, a reduction in V_{ON}, results in a vertical shrinking of the viewing zone.

FIG. 9 is a computer simulation graph illustrating the contrast ratios of the aforesaid display wherein the retardation value of the front and rear retardation films is 320 nm, and the parameter V_{ON} is 6.8 volts. The difference between the graph of FIG. 7 and the graph of FIG. 9 is that a green wavelength of 550 nm was used in FIG. 9. The reason for the higher contrast for the green wavelength as opposed to the red wavelength of FIG. 7 is that the cell gap of 5.70 μm is more nearly matched to the first transmission minimum for the green wavelength than that of the red wavelength. Accordingly, the green wavelength experiences higher contrast ratios in the center of its viewing zone. Again, the 10:1 contrast ratio curve in FIG. 9 extends horizontally along the 0° vertical viewing axis a total of about 75°.

FIG. 10 is a computer simulation graph of the aforesaid display wherein a blue wavelength of 480 nm was used. As in the graphs of FIGS. 7–9, the retardation value for the rear and front retardation films or plates was 320 nm. The 10:1 blue contrast ratio curve shown in FIG. 10 extends horizontally along the 0° vertical viewing axis a total of about 75°. The blue contrast ratio viewing zone is shifted slightly upward from that shown in FIG. 7 with respect to the red wavelength.

As can be seen from the contrast ratio curves of FIGS. 1, 2, and 7–10, it would be highly desirable if one could provide a normally white liquid crystal display with a viewing zone including contrast ratio curves which extended to large horizontal and vertical viewing angles.

U.S. Pat. No. 4,984,874 discloses a liquid crystal display device having front and rear retardation films having retardation values of about 300 nm. A liquid crystal layer including front and rear buffing zones is sandwiched between the retardation films. The rear retardation film functions so as to convert linearly polarized light into elliptically polarized light while the front retardation film converts elliptically polarized light exiting the liquid crystal material into linear polarized light before it reaches the front or exit polarizer. The twist angle of the liquid crystal material of U.S. Pat. No. 4,984,874 is about 180°–270°.

U.S. Pat. No. 5,107,356 discloses a normally black liquid crystal display including first and second polarizers having parallel transmission axes. A liquid crystal material of this patent is sandwiched between front and rear retardation films.

While it is known to dispose rear and front 300–600 nm retardation films or plates on opposite sides of a liquid crystal layer of a P-buffed display, the prior art does not disclose providing a normally white X-buffed liquid crystal display or pixel with rear and front retardation films having 80–200 nm retardation values in order to achieve a high contrast ratio over a predetermined range of viewing angles. The prior art also does not disclose symmetrically rotating the optical axes of such rear and front retardation films so as to shift the centered position of the display's viewing zone to a point below the 0° vertical viewing axis, and thus, away from inversion areas present above the 0° vertical viewing axis.

The terms "clockwise" and "counterclockwise" as used herein mean as viewed from the viewer's or observer's side of the liquid crystal display or pixel.

The term "rear" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones, retardation films, and orientation films means that the described element is on the incident light side of the liquid crystal material, or in other words, on the side of the liquid crystal material opposite the viewer.

Each of the displays and light valves described herein is/was "X-buffed" unless otherwise shown or described.

The term "front" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones, retardation films, and orientation films means that the described element is located on the viewer side of the liquid crystal material.

The LCDs and light valves of FIGS. 1–3 and 7–45 herein include left handed liquid crystal material with a birefringence (ΔN) of 0.084 at room temperature.

The term "retardation value" as used herein means "d·ΔN" of the retardation film or plate, wherein "d" is the film thickness and "ΔN" is the film birefringence (either positive or negative).

The term "interior" when used herein to describe a surface or side of an element, means the side or surface closest to the liquid crystal material.

The term "light valve" as used herein means a liquid crystal display pixel including a rear polarizer, a rear retardation film (unless otherwise specified), a rear transparent substrate, a rear continuous electrode, a rear orientation film, a LC layer, a front orientation film, a front continuous pixel electrode, a front substrate, a front retardation film (unless otherwise specified), and a front polarizer in that order, without the presence of color filters and driving active matrix circuitry such as TFTs.

The term "contrast ratio" as used herein means the transmission of light through the display or pixel in the OFF

or white state versus the amount of transmission through the display or pixel in the ON or darkened state.

It is apparent from the above that there exists a need in the art for a normally white liquid crystal display wherein the viewing zone of the display includes high contrast ratios at extended or large vertical and horizontal viewing angles. There also exists a need in the art to center the viewing zone of a NW LCD at a position distant from inversion areas present at or above the 0° vertical viewing axis.

SUMMARY OF THE INVENTION

Generally speaking this invention fulfills the above-described needs in the art by providing a liquid crystal display comprising:

- a plurality of pixels, each of these pixels being comprised of a pair of driving electrodes and a twisted nematic liquid crystal material located therebetween, the liquid crystal material being of a thickness "d" and having an anisotropy ΔN such that the product of d·ΔN is about 400–550 nm and wherein the liquid crystal material is capable of twisting at least one normally incident visible wavelength of light passing therethrough in an amount of about 80°–100°;
- a rear, light-entrance polarizer having a transmission axis oriented in a first direction;
- a front, light-exit polarizer having a transmission axis oriented in a second direction with respect to the first direction thereby to define a normally white display;
- a rear retardation film disposed between the rear polarizer and the twisted neatic liquid crystal material;
- a front retardation film disposed between the front polarizer and the liquid crystal material; and
- wherein the transmission axes of the polarizers and optical axes of the retardation films are so arranged each with respect to the others so as to achieve a white light contrast ratio of at least about 10:1 over a horizontal angular span of at least about 100° and over a vertical angular span of greater than about 55°.

In the preferred forms of this invention contrast ratios of at least about 10:1 over a horizontal angular span of at least about 120° and over a vertical angular span greater than about 60° are achieved; particlarly when about 6.0 volts is applied to the display.

In still further preferred forms of this invention the above-described 10:1 contrast ratios are achieved while at same time 30:1 contrast ratios of at least about 80° the horizontal angular span and about 30° over the vertical angular span are also achieved. In a particularly preferred form of this invention, furthermore, not only are the above-described ratios achieved but a contrast ratio of about 50:1 is also achieved over a horizontal angular span of about 85° and over a vertical angular span of about 30°. In such embodiments, furthermore, it is preferred to design the display so that the product of

$$\frac{d \cdot \Delta N}{\lambda}$$

is approximately matched to the first minimum of a single, *pre-selected color whose wavelength is λ. Such a color is* usually red, green, or blue, but may be any other color desired.

In addition, this invention further fulfills the above-described needs in the art by providing a normally white liquid crystal display including a plurality of pixels comprising: a twisted nematic liquid crystal layer which twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough; a first retardation film on a first side of said liquid crystal layer; a second retardation film on a second side of said liquid crystal layer whereby said liquid crystal is disposed between said first and second retardation films; and wherein said first and second retardation films *each are uniaxial and have positive or negative* retardation values of from about 80–200 nm, and wherein the optical axes of the retardation films are so arranged each with respect to the other so as to achieve a high contrast ratio over a predetermined range of viewing angles.

In certain preferred embodiments of this invention, the first and second retardation films each have an optical axis, and wherein the optical axis of the first retardation film defines a first direction and the optical axis of the second retardation film defines a second direction, and wherein the first and second directions are different by about 75°–100°.

In certain other preferred embodiments of this invention the display further includes a first polarizer substantially adjacent the first retardation film and a second polarizer substantially adjacent the second retardation film, whereby the first and second retardation films are disposed between the first and second polarizers.

In certain further preferred embodiments of this invention the display when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 20:1 at viewing angles of about 0° vertical, ±45° horizontal.

In still further preferred embodiments of this invention the display when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 20:1 at viewing angles of about −20° vertical, ±40° horizontal.

This invention further fulfills the above-described needs in the art by providing a pixel for a liquid crystal display comprising: a rear, light-entrance polarizer having a transmission axis oriented in a first direction; a front, light-exit polarizer having a transmission axis oriented in a second direction with respect to the first direction thereby to define a normally white pixel; a rear uniaxial retardation film disposed between the rear polarizer and a twisted nematic liquid crystal material, wherein the liquid crystal material twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough; a front uniaxial retardation film disposed between the front polarizer and the liquid crystal material; and wherein the front and rear retardation films have positive birefringent values and both have retardation values of from about 80–200 nm, and wherein the transmission axes of said polarizers and optical axes of said retardation films are so arranged each with respect to the others so as to achieve a high contrast ratio over a predetermined range of viewing angles.

In still other preferred embodiments of this invention the pixel has a white light contrast ratio when about 6.0 volts is applied to the pixel of at least about 30:1 at viewing angles of about (i) 0° vertical, −40° horizontal; (ii) 0° vertical, 30° horizontal; (iii) 25° vertical, 0° horizontal; and (iv) −5° vertical, ±25° horizontal.

In certain further preferred embodiments of this invention a pixel has a white light contrast ratio when about 6.0 volts is applied to the pixel of at least about 10:1 at viewing angles of about (i) 0° vertical, ±60° horizontal; (ii) 30° vertical, 0° horizontal; and (iii) −15° vertical, ±30° horizontal.

In certain further preferred embodiments of this invention in angle of from about 80°–100° is defined between the optical axes of the rear and front retardation films. In still further preferred embodiments of this invention an angle of from about 85°–90° is defined between the optical axes of the rear and front retardation films.

This invention further fulfills the above-described needs in the art by providing a liquid crystal display having a viewing zone centered substantially below the 0° vertical viewing axis, comprising: a first polarizer having a transmission axis defining a first direction; a second polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another thereby defining a normally white display; a first retardation film having an optical axis and a positive or negative retardation value of from about 80–250 nm; a second retardation film having an optical axis, a twisted nematic liquid crystal layer disposed between the first and second retardation films wherein the liquid crystal layer twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough; wherein the optical axes of the first and second retardation films define an angle δ therebetween of from about 70°–89° thereby creating a display having its highest contrast viewing zone centered substantially below the 0° vertical viewing axis and remote from inversion areas present above said 0° vertical viewing axis when a voltage of from about 5.0–7.0 volts is applied to the liquid crystal layer.

In certain further preferred embodiments of this invention the angle δ between the optical axes of the rear and front retardation films is from about 75°–87° thereby positioning and centering the high contrast viewing zone so as to avoid an inversion area of viewing angles located above the 0° vertical axis viewing angle and wherein said retardation films are positively birefringent.

In still further preferred embodiments of this invention the optical axis of the first retardation film and the transmission axis of the first polarizer define an angle Θ1 between the rear retardation film optical axis and the rear polarizer transmission axis of from about 1.5°–7.5° therebetween.

In still further preferred embodiments of this invention the optical axis of the second retardation film and the transmission axis of the second polarizer define an angle Θ2 between the front retardation film optical axis and the front polarizer transmission axis of from about 1.5°–7.5° therebetween.

In other preferred embodiments of this invention the angles Θ1 and Θ2 are substantially equal thereby creating a high contrast viewing zone which is substantially symmetrical about the 0° horizontal viewing axis.

This invention further fulfills the above-described needs in the arts by providing a method of shifting the highest contrast viewing zone of a liquid crystal display to a centered position away from an inversion area, comprising the steps of: a) providing the liquid crystal display with a first polarizer having a transmission axis defining a first direction; b) providing the display with a second polarizer having a transmission axis defining a second direction; c) positioning the first and second polarizers on opposite sides of a twisted nematic liquid crystal layer which twists at least one wavelength of normally incident visible light about 80°–100° when it passes therethrough; d) positioning first and second positively birefringent uniaxial retardation films with substantially equal retardation values on opposite sides of the liquid crystal layer wherein the first retardation film is substantially adjacent the first polarizer, and the second retardation film is substantially adjacent the second polarizer; e) orienting an optical axis of the first retardation film relative to the first polarizer axis so as to define an angle Θ1 therebetween; f) orienting an optical axis of the second retardation film relative to the second polarizer axis so as to define an angle Θ2 therebetween; g) selecting values for the Θ1 and Θ2 so as to center the highest contrast viewing zone of the display at a point substantially below the 0° vertical viewing angle axis, thereby positioning and centering the highest contrast viewing zone substantially distant from an inversion area located above the 0° vertical viewing axis.

In certain further preferred embodiments of this invention, the angles Θ1 and Θ2 are selected to be in the range of from about 3°–5°.

In certain further preferred embodiments of this invention, the angles Θ1 and Θ2 are selected to be in the range of from about 2°–10°.

In still further preferred embodiments of this invention, the retardation films are uniaxial and have negative birefringence.

In still other preferred embodiments of this invention, the retardation films are biaxial and are either positively or negatively birefringent.

This invention further fulfills the above described needs in the art by providing a pixel for a twisted nematic liquid crystal display, comprising: a rear, light-entrance polarizer having a transmission axis oriented in a first direction; a front, light exit polarizer having a transmission axis oriented in a second direction wherein said first and second directions are substantially perpendicular to one another thereby defining a normally white display; a rear biaxial retardation film disposed between said rear polarizer and a twisted nematic liquid crystal material, wherein the liquid crystal material twists at least one wavelength of normally incident visible light about 80°–100° as it passes therethrough; a front biaxial retardation film disposed between the front polarizer and the liquid crystal material; wherein the rear retardation film optical axis having the largest index of refraction is oriented in a direction substantially parallel to the first direction of the transmission axis of the rear polarizer, and the front retardation film optical axis having the largest index of refraction is oriented substantially parallel to the second direction of the transmission axis of the front polarizer; and wherein the optical axes of the rear and front retardation films with said largest indices of refraction each have retardation values ($d \cdot \Delta_{zx}$) in the range of from about −100 to −200 nm such that the viewing zone of the pixel has high contrast ratios at large predetermined horizontal viewing angles.

This invention will now be described with respect to certain embodiments thereof, accompanied by certain illustrations, wherein:

IN THE DRAWINGS

FIG. 1 is a contrast ratio graph utilizing white light for a light valve liquid crystal pixel with a voltage of 6.8 volts applied thereto.

FIG. 2 is a contrast ratio curve graph using white light in the prior art light valve of FIG. 1.

FIG. 3 is an intensity versus driving voltage plot of the prior art light valve of FIGS. 1 and 2. This plot or graph illustrates a fairly large inversion hump over a wide range of horizontal viewing angles at driving voltages of about 3.2 volts and greater.

FIG. 4 is a schematic diagram of the optical components of a prior art "P-buffed" normally white twisted nematic liquid crystal display having retardation films with retardation values of at least 300 nm.

FIGS. 5A–5D are specific wavelength contrast curve diagrams or graphs showing viewing angle characteristics of the prior art normally white liquid crystal display of FIG. 4. Each of the FIGS. 5A–5D represent different orientations of the optical axes of the front and rear polarizers of the FIG. 4 normally white display.

FIG. 6 is a graph illustrating the angular relationship between the horizontal and vertical viewing angles dis-

cussed herein, and their relationship with the conventional liquid crystal display angles ϕ and Θ.

FIG. 7 is a computer simulation contrast ratio curve graph of a normally white liquid crystal display having front and rear retardation films with retardation values of 320 nm. The display simulated by FIGS. 7–10 is not prior art to the present invention, but is merely used for the purpose of later comparison to certain embodiments of this invention.

FIG. 8 is a computer simulation contrast ratio graph of the display of FIG. 7 wherein 5.0 volts are applied across the display and the 630 nm wavelength is used.

FIG. 9 is a computer simulation contrast ratio curve graph of the display of FIGS. 7–8 using a green wavelength of 550 nm and applying a voltage of 6.8 volts across the liquid crystal material.

FIG. 10 is a computer simulation contrast ratio curve graph of the display of FIGS. 7–9 using a blue wavelength of 480 nm and applying 6.8 volts across the liquid crystal material.

FIG. 11(*a*) is a schematic diagram of the optical components of a first embodiment of a normally white twisted nematic liquid crystal display of this invention.

FIG. 11(*b*) illustrates the angular relationships between the respective optical axes of the first embodiment of this invention.

FIG. 11(*c*) illustrates the angular relationships of another embodiment of this invention as viewed from the point of view of an observer or viewer of the display.

FIG. 12 is a computer simulation contrast ratio curve graph illustrating the contrast ratios of the first embodiment of this invention when 6.8 volts is applied across the liquid crystal material, 120 nm retarders are used, and the red wavelength of 630 nm is used.

FIG. 13 is a computer simulation contrast ratio curve graph of the first embodiment to this invention when 6.0 volts is applied across the liquid crystal material, 120 nm retarders are used, and the red wavelength of 630 nm is used.

FIG. 14 is a computer simulation contrast ratio graph of a display according to the first embodiment of this invention when a green wavelength of 550 nm is used, 120 nm retarders are used, and 6.8 volts is applied across the liquid crystal material.

FIG. 15 is a computer simulation contrast ratio curve graph of the display according to the first embodiment of this invention using a green wavelength of 550 nm when 6.0 volts is applied across the liquid crystal material and 120 nm retarders are used.

FIG. 16 is a computer simulation graph illustrating the contrast ratio curves of the display according to the first embodiment of this invention when a blue wavelength of 480 nm is used and 6.8 volts is applied across the liquid crystal material the rear and front retardation films have retardation values of 120 nm.

FIG. 17 is a computer simulation contrast ratio curve graph illustrating the contrast ratios of a display according to the first embodiment of this invention when a blue wavelength of 480 nm is used, 120 nm retarders are used, and 6.0 volts is applied across the liquid crystal material.

FIG. 18 is a computer simulation transmission versus driving voltage plot of horizontal viewing angles for the first embodiment of this invention when the rear and front retardation films have retardation values of 120 nm.

FIG. 19 is a computer simulation transmission versus driving voltage plot of vertical viewing angles for the first embodiment of this invention when the rear and front retardation films have retardation values of 120 nm using white light.

FIG. 20 is a computer simulation contrast ratio curve graph of the first embodiment of this invention when a red wavelength of 630 nm is used, 160 nm retarders are used, and 6.8 volts is applied across the liquid crystal material.

FIG. 21 is a computer simulation contrast ratio curve graph for the first embodiment of this invention when a green wavelength of 550 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 160 nm.

FIG. 22 is a computer simulation contrast ratio curve graph of the first embodiment of this invention when a blue wavelength of 480 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 160 nm.

FIG. 23 is a computer simulation contrast ratio curve graph for the first embodiment of this invention when a red wavelength of 630 nm is used, 6.8 volts is applied across the liquid crystal material, and the front and rear retardation films have retardation values of 80 nm.

FIG. 24 is a computer simulation contrast ratio curve graph for the first embodiment of this invention when a green wavelength of 550 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 80 nm.

FIG. 25 is a computer simulation contrast ratio curve graph of the first embodiment to this invention when a blue wavelength of 480 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 80 nm.

FIG. 26 is a white light measured contrast ratio curve graph of a light valve according to the first embodiment of this invention which utilized uniaxial and positively birefringent rear and front retardation values of 120 nm, and 6.8 volts was applied to the light valve.

FIG. 27 is a white light measured contrast ratio curve graph of the light valve of FIG. 26 when 6.0 volts was applied to the light valve and uniaxial and positively birefringent rear and front 120 nm retarders were used.

FIG. 28 is a white light measured contrast ratio curve graph of the light valve of FIG. 26 when 5.0 volts was applied thereto, and uniaxial and positively birefringent rear and front 120 nm retarders were used.

FIG. 29 is a white light measured contrast ratio curve graph of the light valve of FIG. 26 when 4.0 volts was applied thereto, and uniaxial and positively birefringent rear and front 120 nm retardation values were used.

FIG. 30 is a white light measured intensity versus driving voltage plot of the light valve of FIG. 26 when rear and front uniaxial and positively birefringent 120 nm retardation films were used. The plot illustrates the gray level behavior of the light valve pixel at a plurality of horizontal viewing angles along the 0° vertical viewing axis.

FIG. 31 is a white light measured contrast ratio curve graph for a normally white liquid crystal display according to the first embodiment of this invention when rear and front 120 nm retardation films were used and 6.8 volts was applied to the display.

FIG. 32 is a white light measured contrast ratio curve graph of the liquid crystal display of FIG. 31 when rear and front 120 nm retardation films were used and 6.0 volts was applied to the display.

FIG. 33 is a white light measured contrast ratio curve graph of the liquid crystal display of FIG. 31 when rear and front 120 nm retardation films were used and 5.0 volts was applied to the display.

FIG. 34 is a measured contrast ratio curve graph for the normally white liquid crystal display of FIG. 31 when 4.0

volts was applied to the display, white light was used, and the rear and front retardation films were uniaxial and had retardation values of 120 nm.

FIG. 35 is a measured intensity versus driving voltage plot showing the results for various horizontal angles along the 0° vertical viewing axis for the normally white liquid crystal display of FIG. 31 when white light was used, and the rear and front retardation values were 120 nm.

FIG. 36 is a measured contrast ratio curve graph of a liquid crystal display according to the first embodiment of this invention wherein white light was utilized, 120 nm retarders were used, and 6.0 volts was applied to the display.

FIG. 37 is a measured contrast ratio curve of a light valve according to another embodiment of this invention wherein white light was used, 6.8 volts was applied to the pixel, the retardation films values were 120 nm, and the retardation films were rotated −8° symmetrically.

FIG. 38A is a measured contrast ratio curve of the light valve of FIG. 37 when 5.0 V was applied to the light valve.

FIG. 38B is a white light measured intensity versus voltage graph for the light valve of FIGS. 37 and 38A.

FIG. 39 is a measured contrast ratio curve of a liquid crystal display according to this invention wherein white light was used, 120 nm retardation films were used, 6.0 volts was applied to the display, and the retardation films were rotated −3° symmetrically, and the cell gap "d" was about 5.1 μm in the red subpixel and about 5.7 μm in the green and blue subpixels due to color filter thicknesses.

FIG. 40 is a computer simulation contrast ratio curve graph of a normally white liquid crystal display according to another embodiment of this invention wherein the retardation films are rotated +4° symmetrically, 160 nm retardation films are used, a green 550 nm wavelength is used, and 6.8 V is applied.

FIG. 41 is a cross-sectional view of a liquid crystal display pixel according to certain embodiments of this invention.

FIG. 42 is a partial cut-away view illustrating an active matrix liquid crystal display including a plurality of pixels according to certain embodiments of this invention.

FIG. 43 is a computer simulation contrast ratio curve graph of an LCD according to another embodiment of this invention wherein the rear and front retardation films are uniaxial, but have negative birefringent values. The rear and front retardation films of this embodiment both have retardation values of $\Delta_{ZX}=\Delta_{ZY}=-160$ nm where $\Delta_{ZX}=d\cdot(n_Z-n_X)$, where "n" is the index of refraction and "d" is the thickness of the film. Therefore, the optical axes of these films are oriented in the "Z" direction.

FIG. 44 is a computer simulation contrast ratio curve graph of an LCD according to yet another embodiment of this invention where the LCD has a cell gap of 5.7 μm, 6.0 V is applied, and the rear and front retardation films are biaxial with negative retardation values. The rear and front films of this embodiment have retardation values Δ_{ZX} and Δ_{ZY} of −160 nm and −60 nm respectively. A 550 nm wavelength was used in this graph.

FIG. 45 is a measured contrast ratio graph of a light valve pixel according to another embodiment of this invention where 6.0 V was applied, biaxial rear and front retardation films obtained from Allied Signal Corporation were used, and the light valve was "X-buffed."

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS OF THIS INVENTION

FIG. 11(*a*) is a schematic view of the optical components and their respective orientations of a first embodiment of this invention. As shown in FIG. 11(*a*) the normally white "X-buffed" LCD (or pixel) of this embodiment discloses a rear linear polarizer 1 provided at the light incident side of the liquid crystal layer 5, an exit or front linear polarizer 9 provided at the light exit side of the liquid crystal layer 5, a rear retardation film or plate 3 provided between the liquid crystal layer and the rear polarizer 1, and a front retardation film or plate 7 provided between the liquid crystal layer 5 and the front linear polarizer 9. The retardation films of this embodiment preferably are uniaxial and have positive birefringent (ΔN) values. An example of uniaxial positively birefringent retardation films useful in the practice of this invention are films commercially available from, for example, Nitto Corp., Japan, or Nitto Denko America, Inc., New Brunswick, N.J., as Model No. NRF-RF120 (120 nm retarder).

In addition, biaxial retardation films are obtainable, for example, from Allied Signal Corporation, and negatively birefringent uniaxial/biaxial soluble polyimide retardation films are obtainable from the University of Akron and may also be used in certain embodiments of this invention.

Normally incident light 11 is directed toward the rear linear polarizer 1 from a conventional backlighting system such as is disclosed, for example, in U.S. Pat. No. 5,161,041. The liquid crystal material 5 is preferably of the twisted nematic type and twists at least one normally incident visible wavelength of light about 80°–100° (most preferably about 90°) as it passes through the liquid crystal layer 5. The amount of twist provided by the liquid crystal layer depends upon: the wavelength of light propagating therethrough, the thickness "d" of the liquid crystal layer 5, the birefringence of the liquid crystal layer, and the orientation of the rear and front buffing zones. The liquid crystal material or layer is preferably about 4.5–6.0 μm thick and has a birefringent value of 0.084 at room temperature.

Between the rear retardation film 3 and the liquid crystal layer 5 is a rear orientation film 21 which has an orientation axis or buffing zone oriented in a direction B_1. The rear orientation film 21 oriented in direction B_1 acts to align the liquid crystal layer molecules adjacent the rear orientation film in this direction B_1. The display of FIG. 11(*a*) is also provided with a front orientation film 22 or buffing zone having an orientation direction B_2. The direction B_2 of the front orientation film is preferably substantially perpendicular to direction B_1 of the rear orientation film. As is the case with the rear orientation film, the purpose of the front orientation film is to align the liquid crystal molecules along the interface between the liquid crystal layer 5 and the front orientation film in direction B_2. As described hereinafter more fully, the rear orientation direction B_1 is aligned from the lower right to the upper left, and the front orientation direction B_2 is oriented from the upper right to the lower left which are not to be confused with the directions of the buffing in U.S. Pat. No. 5,184,236 shown in FIG. 4 herein. The effect of the alignment of these two orientation films is to provide for a liquid crystal layer twist of about 80°–100° (most preferably about 90°).

The rear linear polarizer 1 is arranged so that its transmission axis P_R is substantially parallel with the orientation or buffing direction B_2 of the front orientation film. The front or exit linear polarizer 9 is arranged so that its transmission axis P_F is substantially perpendicular to the transmission axis P_R of the rear linear polarizer 1. Because the transmission axis P_R of the rear linear polarizer 1 is substantially perpendicular to the orientation or buffing direction B_1 of its adjacent orientation film 21, this defines what is meant by "crossed" buffing (i.e. "X-buffed"). "P" (i.e. parallel) buffing

simply means that the direction of buffing of the buffing film adjacent its respective polarizer is parallel to the direction of polarization. This arrangement of the transmission axes of the rear and front polarizers also defines a twisted nematic normally white liquid crystal display cell in that as light exits the front linear polarizer 9, it may be viewed by a viewer or observer 15 when the display is in the OFF state.

This embodiment utilizes an "X-buffed" optical arrangement because such an arrangement provides superior results with respect to a "P-buffed" orientation. However, a "P-buffed" arrangement could also be used in certain other embodiments of this invention.

The rear retardation film 3, which is preferably but not necessarily of the uniaxial type, has its optical axis R_R arranged in a direction substantially parallel to the transmission axis P_R of the rear linear polarizer 1. Also, the optical axis R_R of the rear retardation film is arranged in a direction substantially perpendicular to the direction B_1 of the rear orientation film. The retardation value ($d \cdot \Delta N$) of the rear retardation film 3 is preferably in the range of about 80–200 nm, more preferably about 100–160 nm, and most preferably about 120–140 nm.

The front and rear retardation films are preferably positioned about equal distances away from the liquid crystal material in this and certain other embodiments of this invention.

The front retardation film 7, which is located on the opposite side of the liquid crystal layer 5 as the rear retardation film 3, is also preferably uniaxial. The optical axis R_F of the front retardation film 7 is preferably oriented in a direction substantially parallel to the transmission axis P_F of the front or exit linear polarizer 9. Also, the optical axis R_F of the front retardation film 7 is preferably oriented in a direction substantially perpendicular to the orientation direction B_2 of the front orientation film. The terms "substantially parallel" and "substantially perpendicular" when used herein but only as used to define the orientation of the optical axes of the rear and front retardation films, means that the axes of the retardation films are arranged in such a manner ± about 10° unless otherwise specified.

The retardation value of the front retardation film 7 is preferably the same as that of the rear retardation film 3. In other words, the retardation value ($d \cdot \Delta N$) of the front retardation film 7 is in the range of about 80–200 nm, more preferably about 100–160 nm and most preferably about 120–140 nm.

The advantages of utilizing about 80–200 nm retardation films according to the teachings of this invention include a resulting larger viewing zone, and the ability to shift the viewing zone vertically away from an inversion area without substantially distorting the viewing zone.

Also, the retardation values of the rear and front retardation films are preferably about the same so as to define a viewing zone substantially symmetrical about the 0° horizontal viewing axis. The greater the difference between the retardation values of the retardation films 3 and 7, the greater the loss of symmetry of the viewing zone about the 0° horizontal viewing axis. This may be desirable in certain embodiments of this invention.

Normally incident white light 11 from a conventional backlighting system is directed towards the normally white liquid crystal display shown by FIG. 11(*a*) and toward the rear linear polarizer 1 and its transmission axis P_R. The rear linear polarizer 1 linearly polarizes the normally incident white light 11 in a direction P_R. After being polarized by the polarizer 1, the light then proceeds toward and through the rear retardation film 3 which has a specific retardation value in the range of about 80–200 nm. After being transmitted through the rear retardation film 3 and being affected by its optical axis R_R, the white light then proceeds through the rear buffing or orientation film having an orientation direction B_1 and into the liquid crystal material 5. When proceeding through the liquid crystal material 5, the twisted nematic material twists the normally incident white light about 80°–100°, most preferably about 90°.

After exiting the liquid crystal layer 5 (with its molecules aligned along the front surface thereof in direction B_2), the light proceeds through color filters (not shown) and into and through the front retardation film 7. The color filters, may, for example, be red, green, blue, white, or combinations thereof as shown and discussed, for example, in U.S. Pat. No. 4,632,514, the disclosure of which is incorporated herein by reference. After proceeding through the front retardation film 7 and being affected by its optical axis R_F, the color filtered light approaches the front polarizer 9. When the liquid crystal display is in the unenergized or OFF state (no voltage above V_{th}, the threshold voltage, is applied across the liquid crystal material) the twisted light proceeds through the front polarizer 9 and the display appears bright, white, or colored. When the display is in its energized or ON state (a voltage greater than V_{th} is applied across the liquid crystal material) the light is substantially blocked to a voltage dependent extent by the front polarizer 9 and the display appears darkened to a viewer.

Electrodes provided on each side of the liquid crystal material are conventional in the art and are not shown in the drawings of FIGS. 11(*a*)–11(*c*) for the purpose of simplicity.

FIG. 11(*b*) illustrates the angular relationship between the respective axes of the polarizers, retardation films, and orientation films of the first embodiment of this invention. FIGS. 11(*b*) and 11(*c*) are perspective views from the viewer side of the liquid crystal display. As shown in FIG. 11(*b*), the transmission axis P_F of the front polarizer, the optical axis R_F of the front retardation film, and the orientation direction B_1 of the rear orientation film are about parallel one to the others. Also, the transmission axis P_R of the rear polarizer, the optical axis R_R of the rear retardation film, and the direction B_2 of the front orientation film are also about parallel one to the others. Therefore, an angle of about 90° is defined between the orientations of these two groups of directions as shown in FIG. 11(*b*). Preferably, the angular arrangement shown in 11(*b*) of the first embodiment of this invention provides for a viewing zone substantially symmetrical about the 0° vertical viewing axis or reader.

The +X and +Y directions are illustrated in FIGS. 11(*b*) and 11(*c*), and the +Z direction comes out of the figures toward the viewer or reader.

FIG. 11(*c*) is a perspective view illustrating the angular relationship between the above discussed optical directions in another embodiment of this invention. In this embodiment, the optical axes of the rear and front retardation films 3 and 7 are symmetrically rotated negatively so as to shift the central location of the displays' viewing zone to a position below the 0° vertical viewing axis while substantially preserving its shape. This embodiment of this invention illustrated by FIG. 11(*c*) utilizes the same parameters as those described with respect to the first embodiment of this invention except for the orientations of the optical axes of the retardation films. As in the first embodiment of this invention, the transmission axes P_F and P_R of the front and rear linear polarizers in this embodiment define an angle of about 90° therebetween. Also, the directions B_1 and B_2 are

substantially perpendicular to one another and are about parallel with the transmission axes P_F and P_R of the front and rear polarizers respectively.

The difference between the first embodiment and this embodiment is that in this embodiment shown in FIG. 11(c) the optical axis R_R of the rear retardation film is rotated so as to define an angle Θ1 between the transmission axis of the rear polarizer and the optical axis R_R of the rear retardation film. Also, the optical axis R_F of the front retardation film in this embodiment is rotated so as to define an angle Θ2 between the transmission axis P_F of the front polarizer and the optical axis R_F of the front retardation film.

As illustrated in FIG. 11(c), the optical axis R_R of the rear retardation film is rotated clockwise relative to directions P_R and B_2, while the optical axis R_F of the front retardation film is rotated counterclockwise relative to directions P_F and B_1. Preferably, the angles Θ1 and Θ2 as shown in FIG. 11(c) are substantially equal to one another thereby defining a viewing zone for the normally white display which is substantially symmetrical about the 0° horizontal viewing axis. Because the optical axis R_F of the front retardation film has been rotated counterclockwise and the optical axis R_R of the rear retardation film has been rotated clockwise to substantially equal extents, the display of this embodiment is said to have its retardation films rotated negatively in a symmetrical manner. The term "symmetrical" means that the angles Θ1 and Θ2 are substantially equal to one another. For example, if the normally white display illustrated by FIG. 11(c) were to have its rear and front retardation film axes "rotated −8° symmetrically," the angles Θ1 and Θ2 each would be about 4° respectively. Therefore, the angle δ between directions R_R and R_F would be about 82° when the retardation films of this embodiment were rotated −8° symmetrically. It should then be clear that if the optical axes of the rear and front retardation films were to be rotated −4° symmetrically, the angles Θ1 and Θ2 would each be about 2°, and the angle δ between the optical axes of the rear and front retardation films would be about 86°.

The purpose of rotating the optical axes R_R and R_F of the rear and front retardation films is to shift the central location of the viewing zone vertically while still substantially maintaining its shape. In the liquid crystal display art, different customers often desire different viewing characteristics such as the position of the viewing zone. Because of different requirements for different customers, it is advantageous to have a display which may have its viewing zone shifted vertically in accordance with a customer's needs simply by rotating the optical axes of the rear and front retardation films. By rotating the optical axes R_R and R_F of the retardation films to a predetermined negative extent symmetrically, the viewing zone, while being substantially maintained with respect to shape, is shifted to a position centered substantially below the 0° vertical viewing axis and, therefore, away from the inversion zones present above the 0° vertical viewing axis. Such shifts with respect to viewing zones are discussed and shown graphically below with reference to this and other embodiments of this invention.

Another embodiment of this invention which is related to the embodiment disclosed in FIG. 11(c) is the situation where the optical axes of the rear and front retardation films are rotated to a predetermined positive value symmetrically. When the optical axes R_R and R_F are rotated, for example, +6° symmetrically, the optical axis R_R is rotated 3° counterclockwise relative to directions P_R and B_2, while retardation axis R_F is rotated 3° clockwise relative to directions B_1 and P_F. Therefore, the rear and front retardation optical axes R_R and R_F define angles Θ1 and Θ2 of about 3° between their axes and the transmission axes of their respective adjacent polarizers. In this situation where the optical axes R_R and R_F are rotated +6° symmetrically, the angle δ is about 96°. When the optical axes of the retardation films are rotated in a positive manner symmetrically, the result is a shifting of the viewing zone to a position centered substantially above the 0° vertical viewing axis.

FIGS. 12–25 are computer simulations of the first embodiment of this invention illustrating the effect of different driving voltages, retardation values, and wavelengths.

FIGS. 12 and 13 are computer simulation contrast ratio curve graphs of the first embodiment of this invention when the red wavelength of 630 nm is used. With respect to FIGS. 12 and 13, the cell gap "d" is 5.70 μm, and the optical axes R_R and R_F of the rear and front retardation films are parallel to the transmission axes of the rear and front linear polarizers respectively. The rear and front retardation films 3 and 7 each have retardation values of 120 nm in the computer simulation graphs of these Figures, as well as FIGS. 14–19.

In FIG. 12, V_{ON} was 6.8 volts and V_{OFF} was 0.9 volts. As can be seen in FIG. 12, the contrast ratios of the red wavelength are extremely good, especially horizontally. The 30:1 contrast ratio curve extends off the graph in both horizontal directions, while the 10:1 contrast ratio curve extends off the graph in the positive vertical direction. The 30:1 contrast ratio curve extends along the 0° vertical viewing axis a total of about 110° from about −55° to +55° horizontal. Furthermore, the 50:1 contrast ratio curve along the 0° vertical viewing axis extends from about −46° to +46°. These are significant improvements over the prior art.

FIG. 13 is a contrast ratio curve graph which used as parameters those described above with respect to FIG. 12 except that V_{ON} was 6.0 volts. As can be seen in FIG. 13, by lowering the parameter V_{ON}, or driving voltage, the viewing zone is diminished vertically and is slightly shifted upward in the positive vertical viewing direction. However, when, in FIG. 13, the driving voltage is 6.0 volts, the 50:1 contrast ratio curve extends along the 0° vertical viewing axis to extents of about ±55° horizontal.

FIGS. 14–15 are computer simulation contrast (or contour) ratio curve graphs utilizing the green wavelength of 550 nm in the display of the first embodiment of this invention. The cell gap "d" with respect to FIGS. 14–15 was 5.70 μm and the rear and front retardation films 3 and 7 had retardation values of 120 nm. FIG. 14 illustrates the case where V_{ON} was 6.8 volts while FIG. 15 had a V_{ON} of 6.0 volts. As shown in FIG. 14, the 50:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis a total of about 90° from horizontal angles of about −45° to +45°. As can be seen in FIG. 15, by decreasing the driving voltage the viewing zone is constricted slightly vertically and is shifted upward to a position centered substantially above the 0° vertical viewing axis.

FIGS. 16–17 are computer simulation contrast ratio curves of the first embodiment of this invention when the blue wavelength of 480 nm was used and the rear and front retardation films had retardation values of 120 nm. In FIGS. 16–17, the cell gap was also 5.70 μm. As was the case with respect to the red and green wavelengths, when V_{ON} is decreased from 6.8 volts (FIG. 16) to 6.0 volts (FIG. 17), the viewing zone shifts upward substantially above the 0° vertical viewing axis and shrinks vertically with respect to the overall vertical angles covered by the 10:1 contrast ratio curve.

FIG. 18 is a driving voltage versus transmission graph illustrating the transmission at various driving voltages in a

range of horizontal viewing angles (−60° to +60°) along the 0° vertical viewing axis. With the exception of the ±60° curves, there is substantially no effect of inversion upon these transmission versus driving voltage curves throughout the gray level driving voltage zones of about 2–6 volts. In other words, throughout the gray level driving voltage zones, when the driving voltage is increased, the transmission is decreased accordingly, thus, providing for good gray level performance along the 0° vertical viewing axis throughout the horizontal angles shown and defined in FIG. 18. One needs simply to compare the graph of FIG. 18 with the graph of prior art FIG. 3 to see that the arrangements of the optical parameters of the first embodiment of this invention decrease the effect of inversion upon various horizontal viewing angles and provide for an improved gray level performing NW liquid crystal display.

The curves of FIG. 19 representing different vertical viewing angles along the 0° horizontal viewing axis have transmission percentages which generally diminish with increases in driving voltage, possibly with the exception of the +40° vertical viewing angle. The effect of inversion is only seen with respect to the vertical viewing angles of +30° to +40°. In other words, throughout a wide range of gray level driving voltages, when the voltage is increased the transmission is decreased accordingly thus providing for excellent gray level performance throughout the vertical range. The cell gap in FIGS. 18–19 was 5.70 μm. It is noted that white light was used in plotting the driving voltage versus transmission curves of FIG. 18 and FIG. 3. The large inversion humps present in FIG. 3 do not appear in FIGS. 18–19, thus, illustrating an improvement of this embodiment over the prior art.

FIGS. 20–22 are computer simulation contrast ratio curve graphs of the first embodiment of this invention when the rear and front retardation films 3 and 7 had retardation values of 160 nm, V_{ON} was 6.8 volts, and the cell gap "d" was 5.70 μm.

FIG. 20 illustrates the case where the red wavelength of 630 nm was used. In comparing the case where the LCD of the first embodiment utilized 160 nm retardation films (FIG. 20) with the case where 120 nm retardation films (FIG. 12) were used, the difference is that when rear and front retardation values of 120 nm were used the contrast ratios extended to further extents in both the horizontal and vertical directions. For example, with respect to the red wavelength of 630 nm shown in FIG. 12 (120 nm retardation films) and FIG. 20 (160 nm retardation films) the 50:1 contrast ratio curve in FIG. 12 extended horizontally a total of about 110° from about −55° horizontal to about +55° horizontal, while in contrast to this, 50:1 contrast ratio curve in the 160 nm case (FIG. 20) extended horizontally to angles of about ±45°. However, the boomerang shape of the viewing zone shown in FIG. 12 was substantially eliminated when the 160 nm retardation films were used as shown in FIG. 20. Also, the 30:1 contrast ratio curve in FIG. 20 extended in some places to extents further than that of the 30:1 curve of FIG. 12. In sum, both cases, one with retardation films of 120 nm and the other with retardation films of 160 nm, exhibited excellent results in that their respective viewing zones extended to large horizontal and vertical viewing angles.

FIG. 21 illustrates the case where the green wavelength of 550 nm was used in the first embodiment of this invention and the rear and front retardation films 3 and 7 had retardation values of 160 nm. This graph shows that the use of 160 nm retardation films in the first embodiment of this invention provided a viewing zone which extended to large viewing angles in both the horizontal and vertical directions.

FIG. 22 illustrates the case where the blue wavelength of 480 nm was used in combination with 160 nm retardation films. In the cases where 160 nm retardation films were used, the viewing zones were diminished slightly with respect to the 120 nm cases, however, the contrast ratio curves are still excellent.

FIGS. 23–25 are computer simulation contrast ratio curve graphs of the first embodiment of this invention when the rear and front retardation films 3 and 7 had retardation values of 80 nm, V_{ON} was 6.8 volts, and the cell gap "d" was 5.70 μm. FIG. 23 illustrates the case where a red wavelength of 630 nm was used. FIG. 24 illustrates the case where the green wavelength of 550 nm was used, and FIG. 25 illustrates the case where the blue wavelength of 480 nm was used. FIGS. 23–25 all represent excellent contrast ratio curves for the first embodiment of this invention when retardation values of 80 nm were used. The displays of FIGS. 12–25 all utilized uniaxial positively birefringent retardation films.

This invention will now be described with respect to certain examples as follows:

EXAMPLE 1

In this first example, an "X-buffed" light valve having a cell gap "d" of 5.86 μm and a liquid crystal birefringence (ΔN) of 0.084 at room temperature was manufactured and tested as follows. The liquid crystal material used is available commercially from E. Merck Ltd. or its U.S. representative EM Industries, Inc., Hawthorne, N.Y. as Model No. ZLI4718. Data resulting from the light valve of this example is illustrated in FIGS. 26–30.

The light valve pixel of this example was similar to the first embodiment of this invention in that the rear linear polarizer had a transmission axis direction about parallel to the optical axis of the rear retardation film, and the optical axis of the front retardation film was about parallel to the transmission axis of the front or exit linear polarizer. The orientation or buffing direction of the rear orientation film was approximately perpendicular to the optical axis of the rear retardation film, and was approximately parallel to the optical axis of the front retardation film. The optical axes of the rear and front retardation films defined an angle δ of about 90° therebetween. The orientation direction of the front orientation film was approximately parallel to the direction of the optical axis of the rear retardation film, and was substantially perpendicular to the direction of the rear orientation film. White light (RGB tri-peaked) was used when testing the light valve of this example (see FIGS. 26–30). The rear and front retardation films were of the uniaxial type and had positive birefringent values. Also, the rear and front retardation films both had retardation values of 120 nm. The temperature was about 35°–40° C.

FIG. 26 illustrates the experimental data when the driving voltage V_{ON} was 6.8 volts and V_{OFF} was 0.2 volts for this example. As can be seen, the 10:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis to about ±50° horizontal thereby defining a total horizontal viewing range along the 0° vertical viewing axis of about 100°. This 100° range is to be compared with the about 77° range shown in prior art FIG. 1, and the about 65° horizontal range shown in prior art FIG. 5D. In other words, the 10:1 contrast ratio curve of this example at 6.8 volts is substantially improved over displays and light valves of the prior art. In this respect, it is also to be noted that the 50:1 contrast ratio curve shown in FIG. 26 extends along the 0° vertical

viewing axis a substantial distance, i.e. over a total angular span of about 75°.

FIG. 27 illustrates the case where V_{ON} was 6.0 volts for the normally white light valve of this first example. When V_{ON} is decreased from 6.8 volts to 6.0 volts, a more realistic V_{ON} was applied to the pixel and the 10:1 contrast ratio curve extended horizontally slightly further than that shown in FIG. 26.

FIG. 28 illustrates the case where V_{ON} was decreased to 5.0 volts for the light valve of this first example. In the case where 5.0 volts was applied to the pixel, the 10:1 contrast ratio curve defines a range of about 112° along the 0° vertical viewing axis. This is significantly greater than the range defined by the 10:1 contrast ratio curves of the prior art described and illustrated herein.

FIG. 29 illustrates the case where V_{ON} was 4.0 volts for the light valve of this first example. When 4.0 volts was applied to the pixel the 10:1 contrast ratio curve substantially extends off the graph in both horizontal directions. However, when the voltage is decreased, as is the case in FIG. 29, the viewing zone shrinks vertically and is shifted slightly upward, a condition generally true with regard to each of the illustrated decreases in voltage.

FIG. 30 is an intensity versus driving voltage plot for this example illustrating the effects of gray level driving voltages for different horizontal viewing angles ranging from −60° to +60° along the 0° vertical viewing axis. As can be seen in FIG. 30, the gray level performance of this pixel is very good in that the inversion humps are relatively small or non-existent for a wide range of horizontal viewing angles defined herein. In other words, the horizontal gray level performance of this light valve is good because as the driving voltage increases, the intensity for the most part decreases accordingly. Therefore, when the driving voltage of this pixel is increased from one gray level voltage to another the intensity of the pixel generally decreases. The improved results illustrated in the graph shown in FIG. 30 are to be compared to the inferior results illustrated in the prior art graph, FIG. 3, where the inversion humps which begin at about 3.2 volts are relatively large and extend up into the range substantially over 200 fL. In short, the gray level characteristics of the light valve of this example are significantly improved over those of the prior art.

EXAMPLE 2

In this second example, a multi-colored liquid crystal display utilizing TFTs as switching devices in an active matrix array was constructed as follows. The normally white "X-buffed" liquid crystal display had a cell gap "d" of about 5.1 μm for the red subpixel which included a red color filter, and a cell gap "d" of about 5.7 μm for the green and blue subpixels which included green and blue color filters respectively. The difference in cell gap for the different subpixels was due to the different thicknesses of the color filters. The birefringence of the LC material was 0.084 at room temperature. The liquid crystal material was purchased from Merck, Model No. ZLI4718. The display had a rear linear polarizer having a transmission axis substantially perpendicular to the transmission axis of the front or exit linear polarizer. A rear retardation film having an optical axis about parallel to the transmission axis of the rear polarizer was sandwiched between the rear polarizer and the liquid crystal material. Likewise, a front retardation film having an optical axis about parallel to the transmission axis of the front polarizer was disposed between the front polarizer and the liquid crystal material. A rear orientation film was provided with an orientation direction about perpendicular to the optical axis of the rear retardation film, and about parallel to the transmission axis of the front polarizer. A front orientation film was provided with an orientation direction substantially parallel to the transmission axis of the rear polarizer, and about perpendicular to the optical axis of the front retardation film.

The optical axes of the rear and front retardation films defined an angle δ of about 90° therebetween. The rear and front retardation films both had retardation values of 120 nm. The front and rear retardation films both had positive birefringent values and were of the uniaxial type purchased from Nitto Denko America Corporation, New Brunswick, N.J. White light was used in testing this display and the measured results are reported in FIGS. 31–35.

FIG. 31 illustrates the contrast ratio curves when a V_{ON} of 6.8 volts was applied to this normally white liquid crystal display. As can be seen, the 10:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis a total of at least about 120°. This range is significantly greater than the ranges defined by the 10:1 contrast ratio curves of the prior art discussed above. Likewise, the 30:1 contrast ratio curve of FIG. 31 extends along the 0° vertical viewing axis to horizontal angles of about ±42° horizontal. The 10:1 contrast ratio curve of this example when 6.8 volts was applied to the display extends vertically along the 0° horizontal viewing axis from about −40° to about +35° vertical. Again, this range defined vertically by the 10:1 contrast ratio curve of this example is significantly improved over that of the prior art.

FIG. 32 illustrates the situation where 6.0 volts was applied to the normally white liquid crystal display of this example. As can be seen in FIG. 32, when 120 nm retardation films are used and 6.0 volts is applied to the display, the 10:1 contrast ratio curve still extends at least a total of about 120° horizontally along the 0° vertical viewing axis. This liquid crystal display clearly exhibits excellent contrast ratio curves over very wide ranges of viewing angles.

FIG. 33 illustrates the situation where 5.0 volts was applied to the display of this example. As shown the 10:1 contrast ratio curve still extends at least a total of about 120° horizontally along the 0° vertical viewing axis when 5.0 volts was applied to the display. The viewing zone, as previously discussed, decreases vertically as the voltage drops.

FIG. 34 illustrates the situation where 4.0 volts was applied to the display of this example. Again, the 10:1 contrast ratio curves still extends off the graph horizontally along the 0° vertical viewing axis defining a range of at least about 120°. Taken together, FIGS. 31–34 illustrate that the inventive normally white display of this example, has excellent contrast ratios over a wide range of driving voltages, especially in the horizontal directions.

FIG. 35 is a driving voltages versus intensity plot for the display of this example when white light was used. This plot is for a range of horizontal viewing angles extending from −60° to +60° along the 0° vertical viewing axis. As shown, there is virtually no inversion at any voltage for the various horizontal viewing angles defined therein. In other words, as the gray level or driving voltages increase, the intensity of light emitted from the display decreases in conjunction therewith, thus, providing excellent gray level performance for the display of this example. The plot of FIG. 35 when compared with that of FIG. 3 highlights how the LCDs of this invention virtually eliminate the inversion humps expe-

rienced in the prior art, which allows the displays of this invention to be satisfactorily used throughout a wide range of gray level voltages.

EXAMPLE 3

An "X-buffed" normally white liquid crystal display was constructed having a cell gap of 5.1 μm for the red subpixel including a red color filter, and 5.7 μm for the green and blue subpixels including green and blue color filters respectively. The ΔN of the liquid crystal material was 0.084 at room temperature. The liquid crystal material was Merck's Mode No. ZLI4718. This liquid crystal display was driven by a conventional TFT active matrix array.

The normally white display included a rear polarizer, a rear retardation film, a rear substrate, a rear electrode, a rear orientation film, a liquid crystal layer, a front orientation film, a front electrode, a front substrate, a front retardation film, and a front or exit polarizer in that order. The transmission axis of the rear polarizer was approximately parallel to the optical axis of the rear retardation film and the orientation direction of the front orientation film. The transmission axis of the front polarizer was approximately parallel to the optical axis of the front retardation film and the orientation direction of the rear orientation film. The optical axes of the rear and front retardation films defined an angle of about 90° therebetween. The retardation values for both the rear and front films was 120 nm. The rear and front retardation films were of the uniaxial type and had positive birefringent values.

FIG. 36 illustrates the contrast ratio curves for this example when white light was applied to the display and a driving voltage of 6.0 volts was applied. As can be seen, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis to horizontal angles of at least about ±60°. Also, the 30:1 contrast ratio curve of this example when 6.0 volts was applied to the display extends along the 0° vertical viewing axis to horizontal angles of about ±44°. These are significant improvements over the prior art. Also, the 10:1 contrast ratio curve as shown in FIG. 36 extends along the 0° horizontal viewing axis to vertical angles of about ±33°. White light was used in obtaining the data generated by this graph.

EXAMPLE 4

In this example a normally white "X-buffed" light valve according to this invention was constructed wherein the optical axes of the rear and front retardation films were rotated −8° symmetrically thereby shifting the viewing zone to a position centered substantially below the 0° vertical viewing axis while maintaining its shape or integrity.

In this example, the light valve was constructed as follows. A rear linear polarizer was provided with a transmission axis P_R defining a first direction. A front linear polarizer was provided having a transmission axis P_F defining a second direction substantially perpendicular to the first direction. The orientation of the rear orientation film was substantially parallel to the second direction defined by the transmission axis P_F of the front polarizer. The orientation direction of the front orientation film was substantially parallel to the transmission axis direction defined by the transmission axis P_R of the rear polarizer.

A rear retardation film of the uniaxial type having a positive birefringent value was disposed between the rear polarizer and the rear orientation film. A front retardation film of the uniaxial type having a positive birefringent value was provided between the front polarizer and the front orientation film.

Because the optical axes of the rear and front retardation films were rotated −8° symmetrically, angles Θ1 and Θ2 were 4° respectively with an angle δ of 82° defining the angle between the optical axes of the rear and front retardation films. In other words, the optical axis R_F of the front retardation film was rotated 4° counterclockwise relative to the transmission axis P_F of the front polarizer. Also, the optical axis R_R of the rear retardation film was rotated clockwise 4° relative to the transmission axis P_R of the rear linear polarizer. Accordingly, the axes of the rear and front retardation films defined an angle of 82° therebetween represented by the angle δ in FIG. 11(*c*).

The rear and front retardation films of this example had retardation values of 120 nm. The liquid crystal material was Model No. ZLI4718 from E. Merck Ltd. The cell gap "d" of a liquid crystal layer was 5.86 μm for the light valve pixel of this example and the LC birefringence was 0.084. The temperature in this example, as in all of the other examples discussed herein, was about 35° C.–40° C. unless otherwise specified.

FIG. 37 is a contrast ratio curve graph illustrating the viewing zone of the light valve of this example when 6.8 volts and white light was applied thereto. As can be seen, the viewing zone is centered at a position about 10° below the 0° vertical viewing axis (i.e. at about the −10° vertical viewing axis) as a result of the −8° symmetrical rotation of the optical axes of the rear and front retardation films.

This example illustrates the situation where the viewing zone of a display or pixel is shifted to a position substantially below the 0° vertical viewing axis while still substantially maintaining the integrity or symmetry of the overall viewing zone. The symmetry of the viewing zone about the 0° horizontal viewing axis is substantially maintained because the rear and front retardation films had substantially equal retardation values.

FIG. 38A illustrates the viewing zone of the light valve of this example when 5.0 volts and white light was applied thereto. As can be seen in FIG. 38A, the viewing zone is still centered about the −10° vertical viewing axis and is provided with excellent contrast ratios at large viewing angles. As a result of the decrease on V_{ON} from 6.8 volts to 5.0 volts, it is seen in FIG. 38A that the viewing zone has been slightly constricted vertically and slightly expanded horizontally about the center of the viewing zone.

The advantage associated with the light valve of this example is that the centered position of the viewing zone of a given liquid crystal display or pixel thereof according to certain embodiments of this invention can be shifted vertically from one position to another while substantially maintaining the symmetry of the viewing zone in accordance with the specific needs of different customers. These shifts of the viewing zone are accomplished by simple rotation, preferably symmetrically, of the optical axes of the rear and front retardation films of certain embodiments of this invention.

FIG. 38B illustrates the inversion hump problem associated with the vertical viewing angles above the 0° vertical viewing axis for the display of this example. The viewing zone of the display of this example is centered at a location below the 0° vertical viewing axis remote from these inversion areas illustrated in FIG. 38B. Thus, gray level performance is improved by centering the viewing zone at a position distant the inversion zone thereby limiting inversion effects to remote viewing angles.

EXAMPLE 5

A multi-colored normally white "X-buffed" liquid crystal display was constructed and tested with white light as follows. The display, including a conventional TFT matrix array, included a rear linear polarizer having a transmission axis defining a first direction, a front or exit linear polarizer having a transmission axis defining a second direction wherein the first and second directions were substantially perpendicular to one another, a rear retardation film between the rear polarizer and the liquid crystal layer and having an optical axis substantially parallel to the transmission axis of the rear polarizer, a front retardation film having an optical axis substantially parallel to the transmission axis of the front polarizer, a rear orientation film having an orientation direction substantially perpendicular to the first direction defined by the transmission axis of the rear polarizer, a front orientation film having an orientation direction substantially perpendicular to the transmission axis of the front polarizer, and finally a liquid crystal layer sandwiched between the orientation films. The rear and front retardation films had positive birefringent values and were of the uniaxial type. Furthermore, the rear and front retardation films each had a retardation value of 120 nm.

The optical axes of the rear and front retardation films were rotated −3° symmetrically. Therefore, with reference to FIG. 11(*c*), angles Θ1 and Θ2 were each 1.5°, and angle δ was 87° in the display of this example.

FIG. 39 is a white light contrast ratio curve graph showing the measured results when the liquid crystal display of this example had a voltage of 6.0 volts applied to the active matrix, V_{OFF} was 0.2 V, and V_{COMM} was 8.14 V. The contrast ratios as shown in FIG. 39 are excellent in that the 10:1 contrast ratio curve extends significantly beyond a horizontal range of 120° along the 0° vertical axis. Furthermore, the 30:1 contrast ratio along the 0° vertical viewing axis defines a total range of about 100° which is significantly more than that of the prior art. The 10:1 contrast ratio curve in the vertical direction covers a range along the 0° horizontal viewing axis of between about −20° vertical and at least about 40° vertical.

As can be seen in FIG. 39, the −3° symmetrical rotation of the retardation films was not enough to shift the viewing zone below the 0° vertical viewing angle axis. This may be due to manufacturing derivations associated with certain optical elements of this display. Nevertheless, the viewing zone and contrast ratios are excellent, both horizontally and vertically.

The cell gap "d" of the display manufactured in this example was 5.1 μm in the red subpixel where a red color filter was provided, and 5.7 μm in both the green and blue subpixels where green and blue color filters were provided respectively. The difference in cell gap "d" between the subpixels is a result, as in the other examples herein, of the different thicknesses of the color filters. In other words, because the red color filter has a thickness greater than the green and blue color filters, the cell gap "d" in the red subpixel is less than that in the green and blue subpixels. The LC material birefringence was 0.084 at room temperature. The left handed liquid crystal material was Merck's Model No. ZLI4718.

EXAMPLE 6

In this example, an "X-buffed" NW light valve pixel was constructed and tested using white light. A rear linear polarizer was provided having a transmission axis defining a first direction and a front linear polarizer was provided having a transmission axis defining a second direction wherein the first and second directions were substantially perpendicular to one another, thus, defining a normally white light valve. A rear retardation film having an optical axis approximately parallel to the transmission axis of the rear polarizer was provided between the rear polarizer and a rear orientation film. The rear orientation film had a buffing or orientation direction substantially parallel to the direction defined by the transmission axis of the front polarizer. A front retardation film having an optical axis about parallel to the transmission axis of the front polarizer was disposed between the front polarizer and a front orientation film. The front orientation film had an orientation or buffing direction substantially perpendicular to that of the rear orientation film.

In this example, the rear and front retardation films were of the biaxial type. Biaxial retardation films can be characterized by two separate retardation values: $d \cdot \Delta_{ZX}$ and $d \cdot \Delta_{ZY}$. The local X optical axes of the rear and front biaxial retardation films in this light valve were oriented about parallel to their closest adjacent polarizer transmission axis. The local X axis of a biaxial retardation film herein means the axis in the direction having the highest index of refraction (n_X is always the largest index of refraction and n_Z is the lowest). The X, Y, and Z directions (axes) of the biaxial retardation films herein are separate and distinguished from the X, Y, and Z directions (FIG. 6) of the display. In this example, the axis having the retardation value of $d \cdot \Delta_{ZX}$=−168 nm had the highest or largest index of refraction. Both the rear and front biaxial retardation films were obtained from Allied Signal Corporation as Sample No. 4.0. The indices of refraction of the biaxial retardation films of this example were n_X=1.4305; n_Y=1.4275; and n_Z=1.4261. The liquid crystal material had a birefringence of 0.084 at room temperature and was Merck's Model No. ZLI4718. The films therefore had retardation values $d \cdot \Delta_{ZX}$=−168 nm and $d \cdot \Delta_{ZY}$=−53.3 nm.

FIG. 45 is a contrast ratio curve graph illustrating the measured results of the light valve of this example. In FIG. 45, V_{ON} was 6.0 V and V_{OFF} was 0.2 V. As shown, the 10:1 contrast ratio curve extends horizontally off the graph along the 0° vertical viewing axis, thus, defining a horizontal viewing range of greater than about 120°. Furthermore, the 30:1 contrast ratio curve defines a total viewing range along the 0° vertical viewing axis of about 95°–100°. This is a significant improvement over the prior art. The 10:1 contrast ratio curve in the vertical direction along the 0° horizontal viewing axis covers a range of about 75°.

This example illustrates that when a light valve according to this invention is provided with biaxial rear and front retardation films, excellent viewing zone and contrast ratios result and constitute a significant improvement over the prior art.

EXAMPLE 7

FIG. 40 is a computer simulation contrast ratio curve graph illustrating a simulated liquid crystal display according to another embodiment of this invention where the optical axes of the rear and front retardation films are rotated +4° symmetrically. Due to this positive rotation, the center of the viewing zone is shifted to a position substantially above the 0° vertical viewing axis. As shown, the viewing zone of this display is centered about the +20° vertical viewing axis because of the +4° symmetrical rotation of the retardation films.

With reference to FIG. 11(*c*), the axis R_F of this embodiment is rotated or oriented clockwise relative to P_F and B_1 defining an angle of 2° therebetween. Also, axes R_R of this

embodiment is oriented counterclockwise 2° relative to P_R and B_2. As a result, the angle δ between the optical axes of the retardation films is 94° due to the +4° symmetrical rotation of the retardation film axis. The display of this embodiment would be desirable in situations where a viewing zone centered above the 0° vertical viewing axis was desired. The simulation of FIG. 40 used a V_{ON} of 6.8 V, a green wavelength of 550 nm, and 160 nm retarders. The transmission axes of the polarizers as opposed to the optical axes of the retardation films may instead be rotated to shift the location of the viewing zone in certain other embodiments of this invention. However, rotation of the polarizer axes does not provide as good of results as does the rotation of the retarder axes.

EXAMPLE 8

FIG. 43 is a computer simulation of a liquid crystal display according to yet another embodiment of a NW "X-buffed" LCD of this invention. This embodiment is similar to that illustrated and described in the first embodiment of this invention except that the rear and front retardation films 3 and 7 are negatively birefringent and uniaxial. The optical axes of these retardation films are oriented in the "Z" direction, or in other words, in a direction approximately perpendicular to the planes defined by the retardation films. The display of this embodiment, simulated by FIG. 43, had a cell gap of 5.70 μm, utilized a wavelength of 550 nm in testing the display, a V_{ON} of 6.0 volts, was "X-buffed," and a temperature of about 30° C.

The rear and front retardation films of this embodiment had retardation values of $d\cdot\Delta_{ZX}=d\cdot\Delta_{ZY}=-160$ nm. These films are "uniaxial" because $d\cdot\Delta_{ZX}=d\cdot\Delta_{ZY}$. The retardation value $d\cdot\Delta_{ZX}$ is defined as meaning $d\cdot(n_Z-n_X)$ where "n" is the index of refraction of a particular axis and "d" is the thickness of the retardation film. The retardation films of this embodiment were negative because the parameter n_X was greater than the parameter n_Z. The X, Y, and Z directions of the biaxial retardation films herein are separate and distinguished from the X, Y, and Z directions defining the coordinates of the display.

The term n_X herein always represents the largest index of refraction, and n_Z always represents the smallest. The rear and front polarizers had transmission axes which are substantially perpendicular to one another. The rear retardation film was disposed between the rear polarizer and the rear orientation film, and the front retardation film is between the front polarizer and the front orientation film. The negatively birefringent uniaxial retardation films of this embodiment are obtainable from the University of Akron and are disclosed in U.S. Pat. No. 5,071,997 as soluble polyimides and/or copolyimides.

As can be seen in FIG. 43, this embodiment achieves outstanding contrast ratios at very large viewing angles. For example, the 50:1 contrast ratio curve on the 0° vertical viewing axis defines a range of almost 100° horizontally. This is a significant improvement over the prior art.

EXAMPLE 9

FIG. 44 is a computer simulation contrast ratio graph of another NW embodiment of this invention which utilizes biaxial front and rear retardation films each having retardation values $d\cdot\Delta_{ZX}=-160$ nm and $d\cdot\Delta_{ZY}=-60$ nm. Because the retardation values are negative, the films have negative birefringence. $d\cdot\Delta_{ZX}$ is defined as $d\cdot(n_Z-n_X)$ wherein n_X is the largest index of refraction in the film and n_Z is the smallest. Therefore, $d\cdot\Delta_{ZX}$ is always the largest retardation value herein. The graph of FIG. 44 was plotted using the parameters of $V_{ON}=6.0$ volts, a LC birefringence of 0.084, a V_{OFF} of 0.9 V, a cell gap of 5.70 μm, a temperature of about 30° C., an "X-buffed" configuration, and a wavelength of 550 nm. The local X' is the axis with the largest index of refaction, or n_X. The local X' optical axis of each retardation film is oriented substantially parallel to the adjacent polarizer transmission axis. In other words, the local X' axis of the rear retardation film is substantially parallel to the transmission axis of the rear polarizer, and the local X' optical axis of the front biaxial retardation film is substantially parallel to the front polarizer transmission axis. The local X' optical axis in this embodiment has the aforesaid retardation value of $d\cdot\Delta_{ZX}=-160$ nm, because n_X was the largest index of refraction. The rear and front polarizer axes define an angle of about 90° therebetween. The axis with the smallest index of refraction, or n_Z, is oriented about perpendicular to the planes defined by the retardation films. As shown in FIG. 44, the embodiment of this invention using the aforesaid biaxial retardation films achieves excellent contrast ratios at large viewing angles. Again, the 50:1 contrast ratio curve along the 0° vertical viewing axis defines a range of about 100° horizontally.

The specific electrodes and substrates present in the displays and light valves of the above described examples are conventional and were not described or shown for purposes of simplicity.

FIG. 41 is a cross-sectional view of the structural arrangement of a typical liquid crystal display pixel envisioned by this invention. For example, the optical arrangement shown and described in FIGS. 11(a)–11(c) may be used in conjunction with the structural arrangement shown in FIG. 41. Normally incident light enters the pixel and first proceeds through rear linear polarizer 1 and is polarized thereby. After proceeding through the polarizer 1, the normally incident light proceeds through the rear retardation film 3 and the rear transparent substrate 19. The transparent substrates 19 and 20 are preferably made of glass, but also may be made of plastic, quartz, or the like. After proceeding through the rear transparent substrate 19, the light then enters the lower pixel electrode 24 and passes therethrough without being substantially optically affected. The light then proceeds through the rear orientation film 21, a liquid crystal layer 5, the front orientation film 22, and the front electrode layer 25. After proceeding through electrode 25, the light then propagates through the front transparent substrate 20, front retardation film 7, and finally comes to the front or exit linear polarizer 9. When the pixel is in the OFF state, the light proceeds through the linear polarizer 9 toward a viewer. However, when the pixel is in the ON or energized state, the exit polarizer 9 absorbs the light of the pixel and the display appears darkened. Also, color filters (not shown) may be provided at any point between the transparent substrates, and preferably between the front substrate 20 and the electrode layer 25 thereby creating a multicolored pixel including a plurality of colored subpixels. It is understood, of course, that retardation films 3 and 7 may also serve as the buffing layers. In such an embodiment films 3 and 7 are replaced and relocated into the location of buffing films 21 and 22 respectively. It is further understood that retarder films 3 and 7 when not replacing buffing films 21 and 22 may be relocated so as to be between their respective driving electrode (24 and 25) and glass substrate (19 and 20) respectively. By arranging the optical elements of this structural arrangement (FIG. 41) as taught by certain optical embodiments of this invention, the aforesaid improved

contrast ratios over predetermined ranges of viewing angles may be achieved.

An alternative structural arrangement envisioned by this invention, is a normally white pixel similar to the one shown in FIG. 41, except that the rear and front retardation films 3 and 7 are disposed between the substrates 19 and 20. The rear retardation film is sandwiched between, for example, the rear substrate 19 and the rear electrode 24, and the front retardation film is disposed between the front substrate 20 and the front electrode 25. All embodiments of this invention may be practiced in such a structural arrangement with excellent contrast ratios over a large range of viewing angles being realized.

Furthermore, the retardation films according to certain embodiment of this invention may be personalized or patterned according to the wavelength or color of each subpixel as taught by our commonly owned copending patent application filed Dec. 2, 1993 entitled "Liquid Crystal Display With Patterned Retardation Films," Ser. No. 08/160,731, the disclosure of which is incorporated hereby by reference. In other words, a retardation film within a red subpixel may have a retardation value different than a retardation film in a green or blue subpixel.

FIG. 42 is a partial cut-away view of a typical active matrix liquid crystal pixel array as envisioned by this invention. Herein, the rear and front retardation films, which are not specifically shown in FIG. 42, are sandwiched between their adjacent polarizers 1 and 9, and their adjacent substrates 19 and 20. The individual pixels 30 shown in FIG. 42 are driven by conventional TFTs 31 which act as switching devices to selectively drive each pixel 30. Conventional transparent ITO electrodes 33 connect the individuals TFTs 31 to their respective pixels 30. Parallel conductive row lines 35 drive either the gate or drain electrodes of the TFTs 31. Column lines 37 drive the other of the gate and drain electrodes of a TFTs thereby selectively driving the individual pixels 30 when a specific TFT has both its gate and drain electrodes energized.

The simulations, light valves, and displays of FIGS. 7–45 herein were twelve o'clock buffed. Therefore, the rear orientation or buffing directions went from the lower right to the upper left, and the front orientation or buffing direction went from the upper right to the lower left.

The pretilt angle of the displays, light valves, and simulations of FIGS. 1–3 and 7–45 herein is about 3°, and the value of "d/p" (thickness/natural pitch of the liquid crystal material) of the liquid crystal layer of these Figures is set to about 0.25.

The computer simulations herein were conducted using simulation software written by Dr. Dwight Berreman, Scotch Plains, N.J. The software is described and referenced in one of Dr. Berreman's publications titled "Numerical Modelling of Twisted Nematic Devices," Phil. Trans. R. Soc. Lond. A309, 203–216 (1983) which was printed in Great Britain.

Once given the above disclosure, many other features, modifications, and improvements will become apparent to the skilled artisan. Such other features, modifications, and improvements are, therefore, considered to be a part of this invention, the scope of which is to be determined by the following claims:

We claim:

1. A pixel for a liquid crystal display comprising:

a rear, light-entrance polarizer having a transmission axis oriented in a first direction;

a front, light-exit polarizer having a transmission axis oriented in a second direction with respect to said first direction thereby to define a normally white pixel;

a rear uniaxial retardation film disposed between said rear polarizer and a twisted nematic liquid crystal material, wherein said liquid crystal material twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough;

a front uniaxial retardation film disposed between said front polarizer and said liquid crystal material;

wherein said front and rear retardation films each have positive birefringent values and each have retardation values of from about 80–200 nm; and

wherein the transmission axes of said polarizers and optical axes of said retardation films are so arranged each with respect to the others so as to achieve a high contrast ratio over a predetermined range of viewing angles.

2. The pixel of claim 1, wherein said optical axis of said rear retardation film is substantially parallel±about 10° to said rear polarizer transmission axis oriented in said first direction, and said optical axis of said front retardation film is substantially parallel±about 10° to said front polarizer transmission axis oriented in said second direction, thereby defining an angle of from about 70°–110° between the optical axes of the rear and front retardation films.

3. The pixel of claim 2, wherein said front and rear retardation films each have retardation values of from about 100–160 nm.

4. The pixel of claim 2, further including rear and front orientation means for aligning molecules of the liquid crystal material, wherein said rear orientation means has a buffing or orientation direction about parallel to said second direction and said front orientation means has a buffing or orientation direction about parallel to said first direction.

5. The pixel of claim 4, wherein the thickness of the liquid crystal layer is from about 4.5–6.5 μm, and the birefringence of the liquid crystal material is from about 0.075–0.095.

6. The pixel of claim 2, wherein said contrast ratio when about 6.0 volts is applied to said pixel is at least about 30:1 at viewing angles of one of: about i) 0° vertical, −40° horizontal; ii) 0° vertical, 30° horizontal; iii) 25° vertical, 0° horizontal; and iv) −5° vertical, ±25° horizontal.

7. The pixel of claim 2, wherein said contrast ratio when about 6.0 volts is applied to said pixel is at least about 10:1 at viewing angles of about i) 0° vertical, ±60° horizontal; ii) 30° vertical, 0° horizontal; and iii) −15° vertical, ±30° horizontal.

8. The pixel of claim 2, wherein an angle of from about 80°–100° is defined between said optical axes of said rear and front retardation films.

9. The pixel of claim 8, wherein an angle of from about 85°–90° is defined between said optical axes of said rear and front retardation films.

10. The pixel of claim 9, wherein an angle of from about 88°–90° is defined between said optical axes of said rear and front retardation films.

11. The pixel of claim 10, wherein an angle of about 90° is defined between said optical axes of said front and rear retardation films, whereby said optical axis of said rear retardation film is about parallel to said rear polarizer transmission axis and said optical axis of said front retardation film is about parallel to said front polarizer transmission axis.

12. The pixel of claim 2, wherein said front and rear retardation films each have retardation values of from about 120–160 nm.

13. The pixel of claim 2, wherein said front and rear retardation films each have substantially equal retardation values.

14. The pixel of claim 13, wherein the retardation value of each of the rear and front retardation films is about 120 nm.

15. The pixel of claim 2, wherein said pixel when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 30:1 at viewing angles of about −10° vertical, ±40° horizontal.

16. The pixel of claim 2, wherein said pixel when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 30:1 at viewing angles of about −20° vertical, ±30° horizontal.

17. A normally white liquid crystal display including a plurality of pixels, comprising:

a twisted nematic liquid crystal layer which twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough;

a first retardation film on a first side of said liquid crystal layer;

a second retardation film on a second side of said liquid crystal layer whereby said liquid crystal layer is disposed between said first and second retardation films; and

wherein said first and second retardation films each are uniaxial and have positive or negative retardation values of from about 80–200 nm; and

wherein the optical axes of said retardation films are so arranged each with respect to the other so as to achieve a high contrast ratio over a predetermined range of viewing angles.

18. The display of claim 17, wherein said first and second retardation films each have an optical axis, and wherein said optical axis of said first retardation film defines a first direction and said optical axis of said second retardation film defines a second direction, and wherein said first and second directions are different by about 75°–100°.

19. The display of claim 18, wherein said first and second directions are different by about 80°–90°.

20. The display of claim 19, further including a first polarizer substantially adjacent said first retardation film and a second polarizer substantially adjacent said second retardation film, whereby said first and second retardation films are disposed between said first and second polarizers.

21. The display of claim 20, wherein a transmission axis of said first polarizer is substantially parallel to said optical axis of said first retardation film, and a transmission axis of said second polarizer is substantially parallel to said optical axis of said second retardation film, whereby said transmission axes of said first and second polarizers are about perpendicular to one another.

22. The display of claim 21, further comprising a first liquid crystal orientation means disposed between said first retardation film and said liquid crystal material, wherein said first orientation means has a buffing or orientation direction substantially parallel to said transmission axis of said second polarizer, and wherein said retardation films have positive birefringent values and then positive retardation values.

23. The display of claim 22, further comprising a second liquid crystal orientation means disposed between said second retardation film and said liquid crystal material, wherein said second orientation means has a buffing or orientation direction substantially parallel to said transmission axis of said first polarizer, whereby said first and second orientation means have respective buffing or orientation directions which are about perpendicular to one another.

24. The display of claim 23, wherein said first and second retardation films each have retardation values of from about 120–160 nm.

25. The display of claim 24, wherein said first and second directions are different by about 88°–90°.

26. The display of claim 25, wherein said first and second directions are different by about 90°.

27. The display of claim 18, wherein said display when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 20:1 at viewing angles of about 0° vertical, ±45° horizontal.

28. The display of claim 18, wherein said display when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 20:1 at viewing angles of about −20° vertical, ±40° horizontal.

29. The display of claim 18, wherein said display when about 5.0 volts is applied thereto has a white light contrast ratio of at least 10:1 at viewing angles of about −20° vertical, ±60° horizontal.

30. The display of claim 17, wherein said first and second retardation films have negative birefringent values and thus have negative retardation values.

31. A liquid crystal display having a viewing zone centered substantially below the 0° vertical viewing axis, comprising:

a first polarizer having a transmission axis defining a first direction;

a second polarizer having a transmission axis defining a second direction wherein said first and second directions are substantially perpendicular to one another thereby defining a normally white display;

a first retardation film having an optical axis and a positive or negative retardation value of from about 80–250 nm;

a second retardation film having an optical axis;

a twisted nematic liquid crystal layer disposed between said first and second retardation films wherein said liquid crystal layer twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough;

wherein said optical axes of said first and second retardation films define an angle δ therebetween of from about 70°–89° thereby creating a display having its highest contrast viewing zone centered substantially below the 0° vertical viewing axis and therefore remote from inversion areas present above said 0° vertical viewing axis when a voltage of from about 5.0–7.0 volts is applied to said liquid crystal layer.

32. The display of claim 31, wherein said angle δ is from about 75°–87° thereby positioning and centering the high contrast viewing zone so as to avoid an inversion area of viewing angles located above the 0° vertical axis viewing angle, and wherein said retardation films are uniaxial and positively birefringent.

33. The display of claim 32, wherein said optical axis of said first retardation film and said transmission axis of said first polarizer define angle Θ1 of from about 1.5°–7.5° therebetween.

34. The display of claim 33, wherein said optical axis of said second retardation film and said transmission axis of said second polarizer define an angle Θ2 of from about 1.5° to 7.5° therebetween.

35. The display of claim 34, wherein said angles Θ1 and Θ2 are substantially equal thereby creating a high contrast viewing zone which is substantially symmetrical about the 0° horizontal viewing axis.

36. The display of claim 35, wherein said display has at least a contrast ratio of about 100:1 at the viewing angle of about −10° vertical, 0° horizontal.

37. The display of claim 35, wherein said display has at least a contrast ratio of about 80:1 at the viewing angles of about −10° vertical, ±10° horizontal.

TAB 2

US005694187A

United States Patent [19]

Abileah et al.

[11] Patent Number: 5,694,187

[45] Date of Patent: *Dec. 2, 1997

[54] LCD INCLUDING A NEGATIVE BIAXIAL RETARDER ON EACH SIDE OF THE LIQUID CRYSTAL LAYER

[75] Inventors: Adiel Abileah, Farmington Hills; Gang Xu, Royal Oaks, both of Mich.

[73] Assignee: OIS Optical Imaging Systems, Inc., Northville, Mich.

[*] Notice: The term of this patent shall not extend beyond the expiration date of Pat. No. 5,570,214.

[21] Appl. No.: 785,900

[22] Filed: Jan. 21, 1997

Related U.S. Application Data

[63] Continuation of Ser. No. 711,797, Sep. 10, 1996, which is a continuation of Ser. No. 167,652, Dec. 15, 1993, Pat. No. 5,570,214.

[51] Int. Cl.^{6} G02F 1/1335

[52] U.S. Cl. 349/120; 349/118

[58] Field of Search 349/118, 120, 349/119

[56] **References Cited**

U.S. PATENT DOCUMENTS

5,032,008	7/1991	Yamamoto et al.	349/119
5,124,824	6/1992	Kozaki et al.	349/120
5,189,538	2/1993	Arakawa	349/120
5,227,903	7/1993	Miyazawa et al.	349/118
5,369,513	11/1994	Akatsuka et al.	349/118
5,440,413	8/1995	Kikuchi et al.	349/119
5,550,661	8/1996	Clark et al.	349/117
5,550,662	8/1996	Bos	349/117
5,570,214	10/1996	Abileah et al.	349/117

Primary Examiner—Anita Pellman Gross
Attorney, Agent, or Firm—Myers Liniak & Berenato

[57] **ABSTRACT**

A normally white twisted birefringent liquid crystal display having first and second retardation films having retardation values of about 80–200 nm on opposite sides of a liquid crystal layer for the purpose of expanding the viewing angles of the display. Also, the viewing zone of this normally white display can be shifted vertically by rotating the optical axes of the retardation films so as to position the viewing zone away from an inversion area.

5 Claims, 46 Drawing Sheets

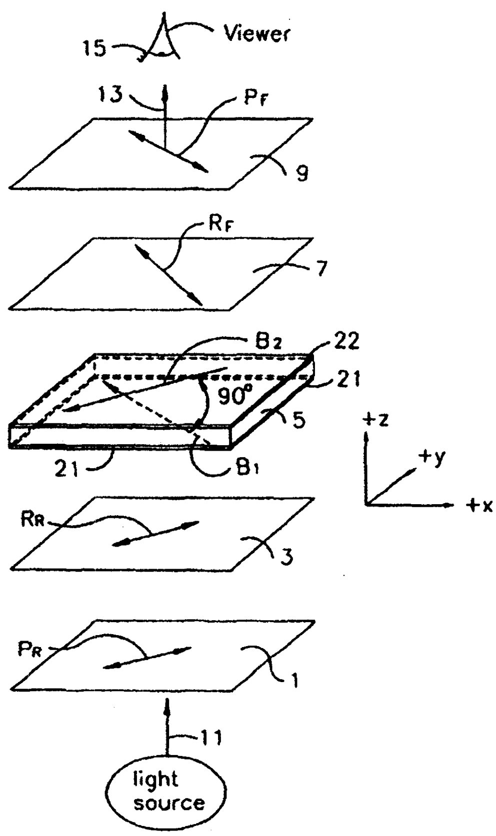


FIG. 1 (Prior Art)

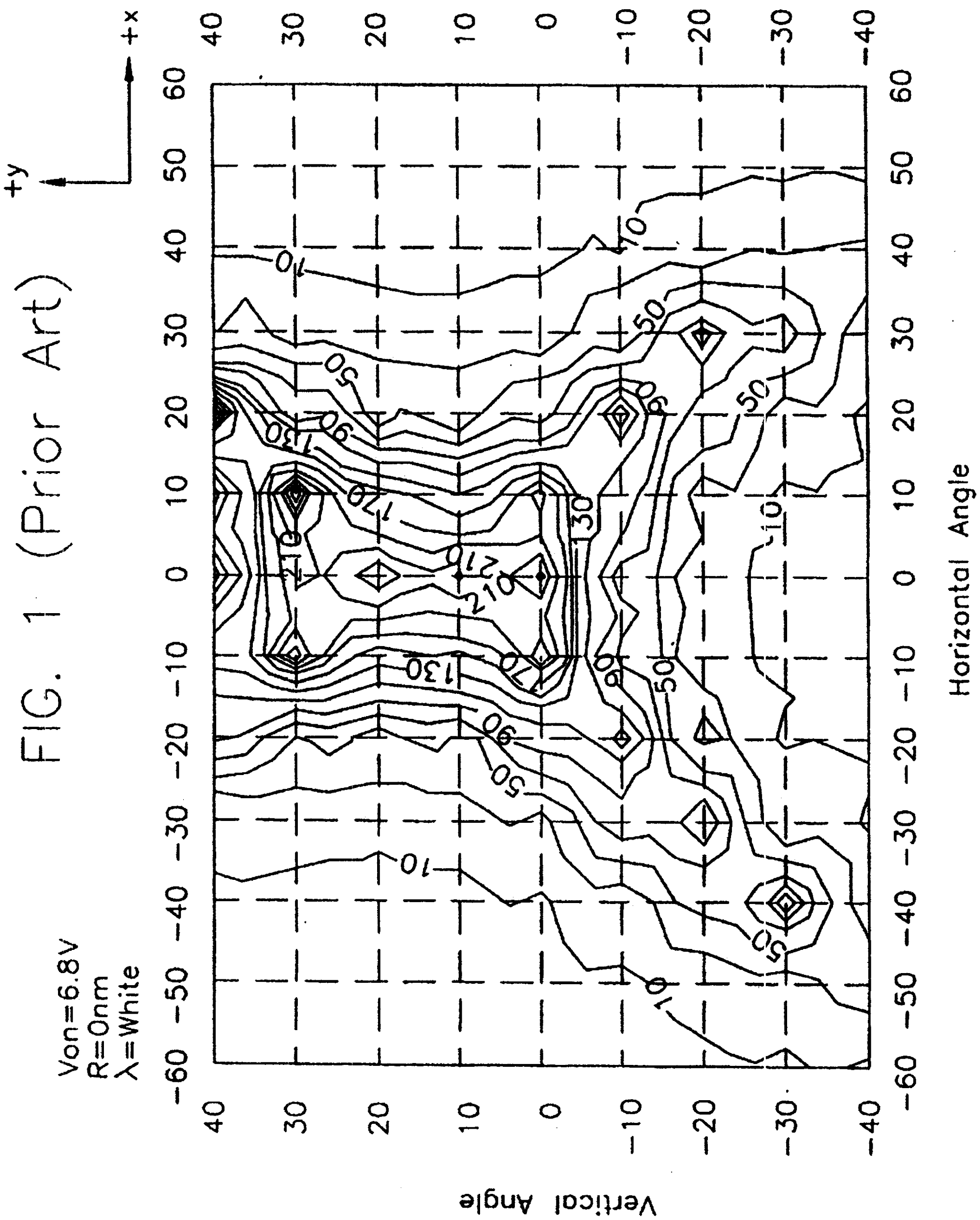


FIG. 2 (Prior Art)

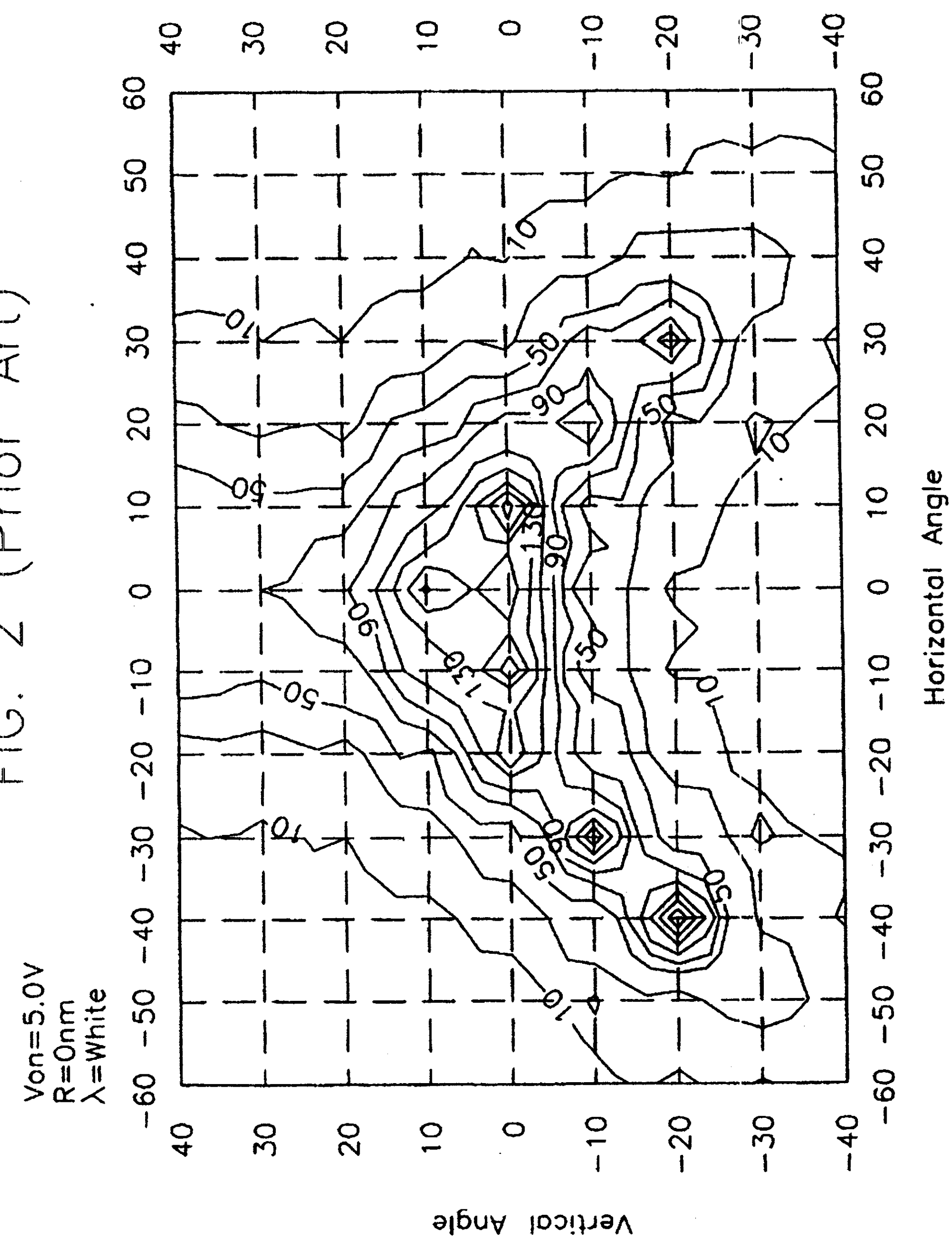


FIG. 3 (Prior Art)

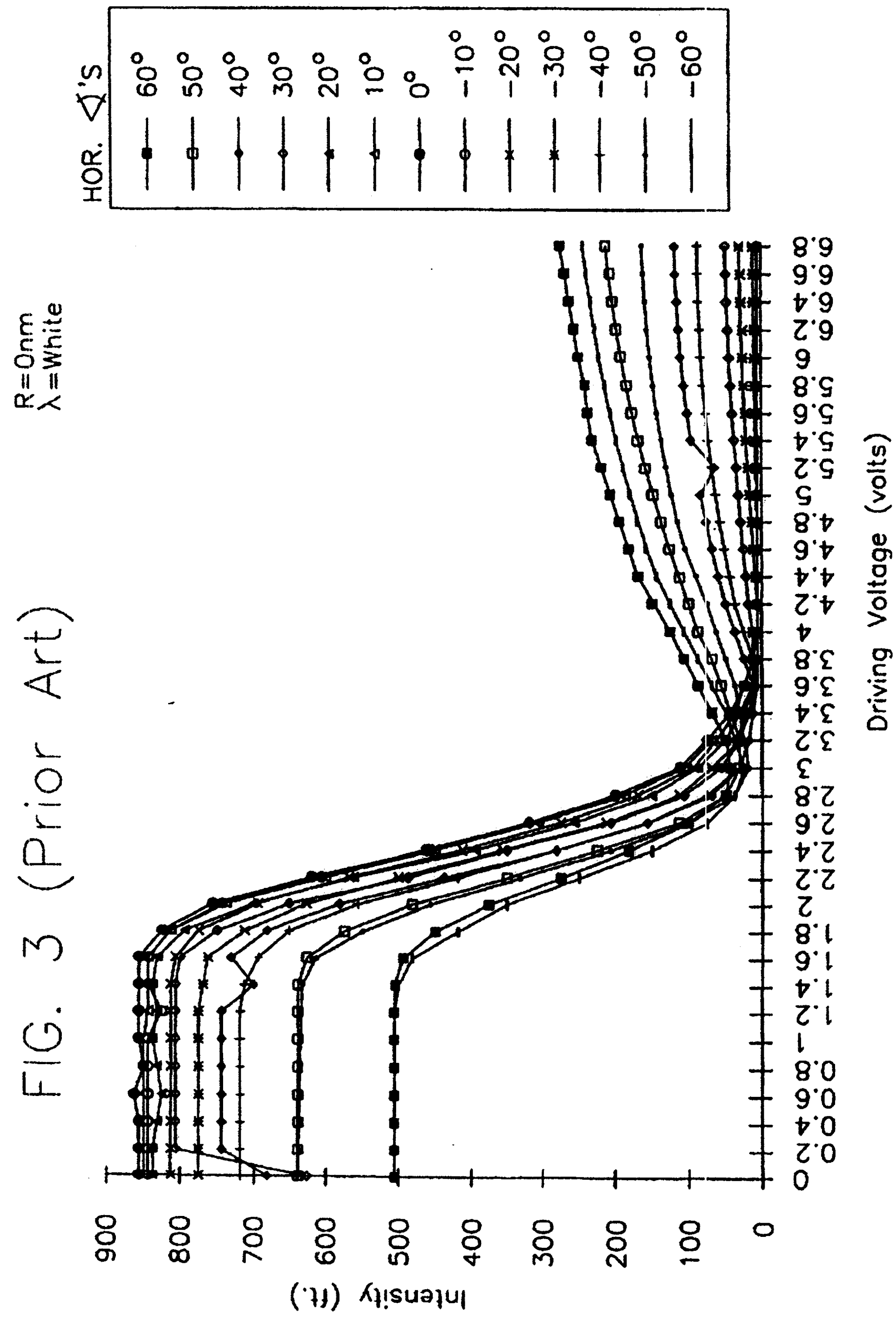
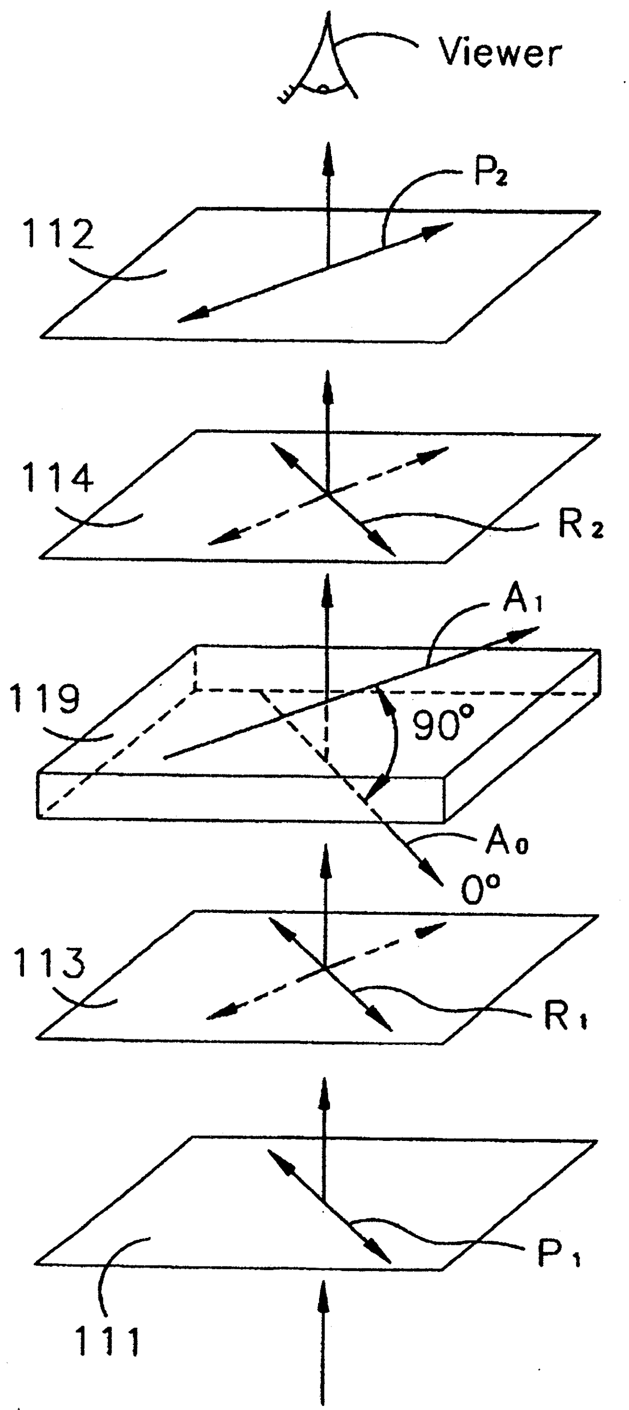


Fig. 4 (Prior Art)



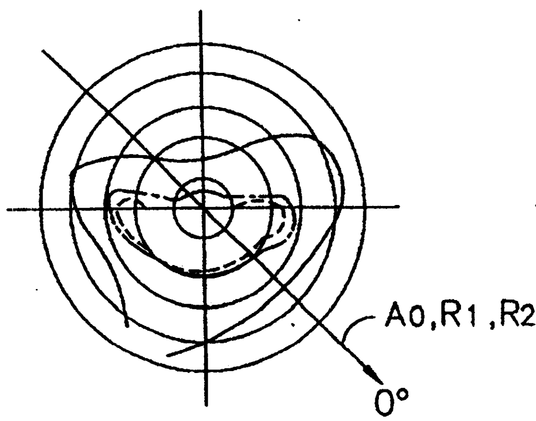


Fig. 5A (Prior Art)

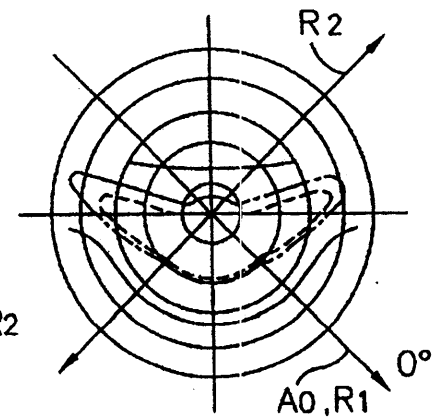


Fig. 5B (Prior Art)

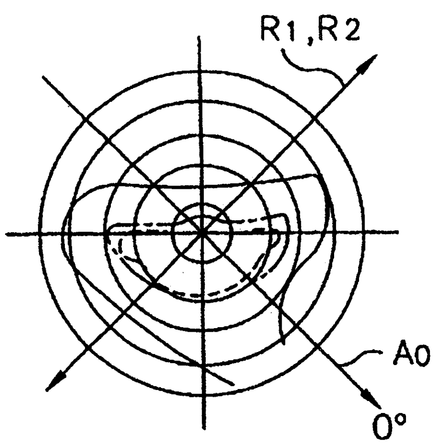


Fig. 5C (Prior Art)

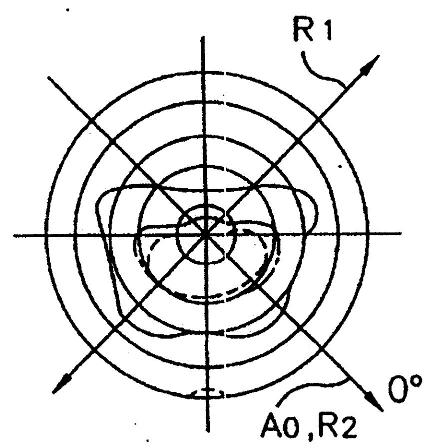


Fig. 5D (Prior Art)

--------- 100:1

-- —— -- 50:1

———— 10:1

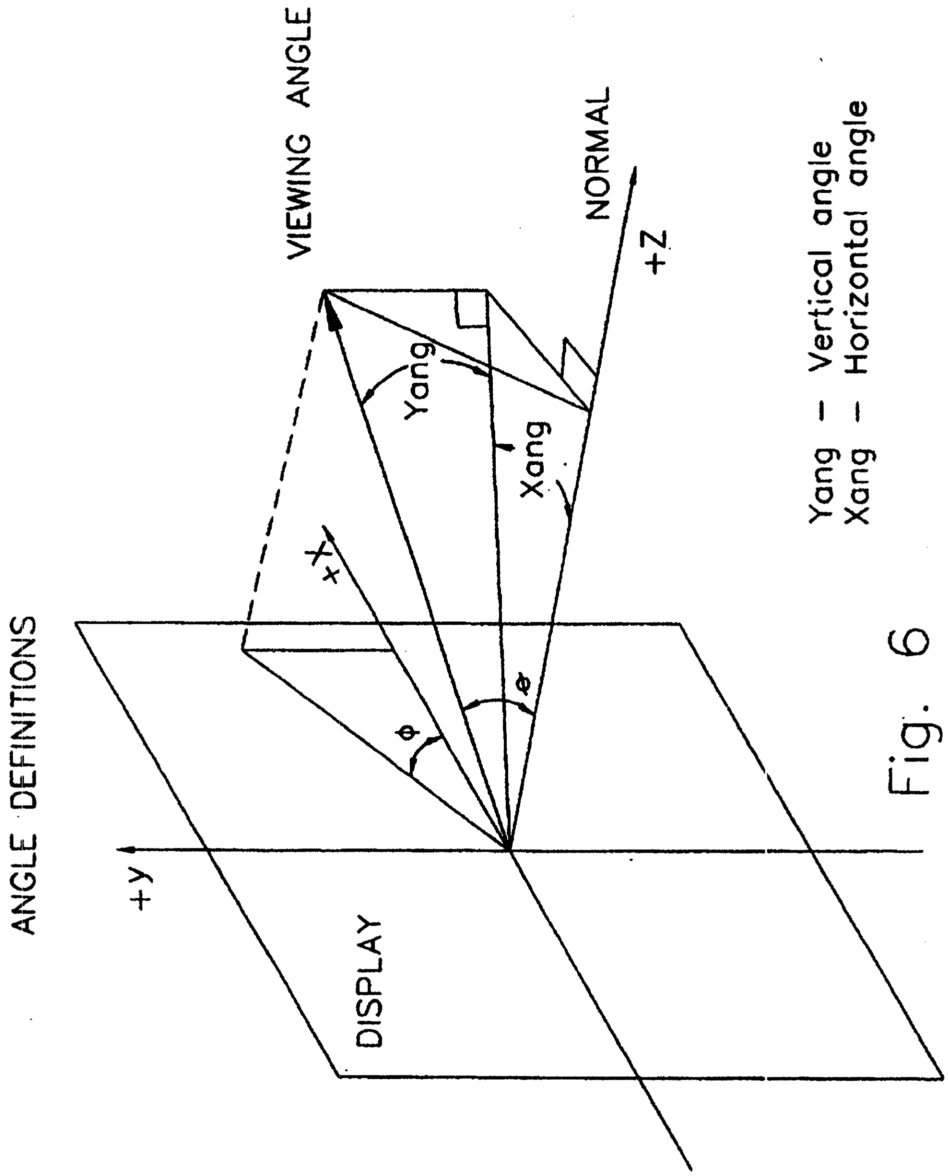

ANGLE DEFINITIONS
VIEWING ANGLE
NORMAL
+Z
+X
+y
DISPLAY
Yang
Xang
ϕ
ϕ
Yang – Vertical angle
Xang – Horizontal angle

Fig. 6

FIG. 7

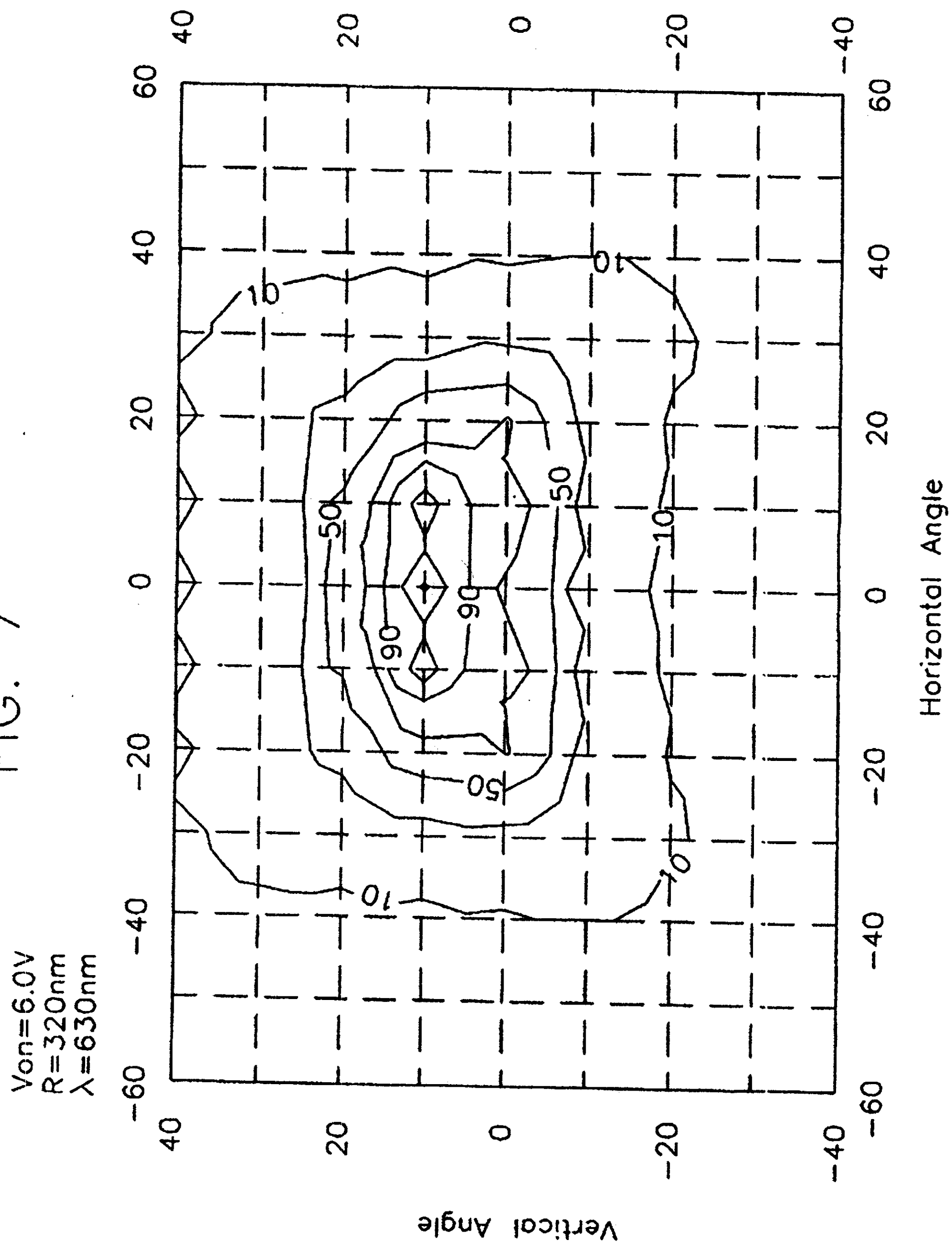
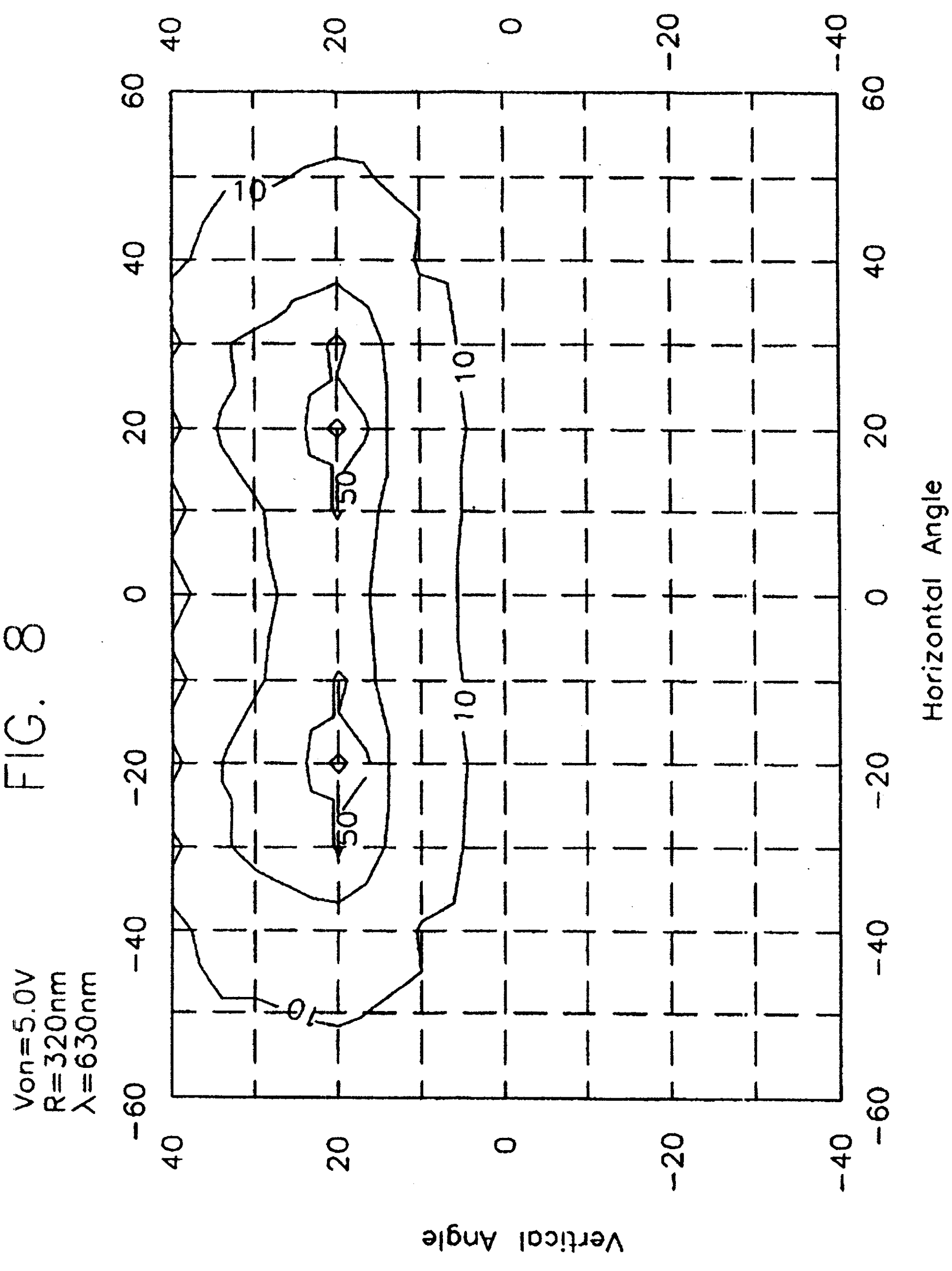

Von=6.0V
R=320nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
90

FIG. 8



Von=5.0V
R=320nm
λ=630nm
10
50
Horizontal Angle
Vertical Angle

FIG. 9

Von=6.8V
R=320nm
λ=550nm

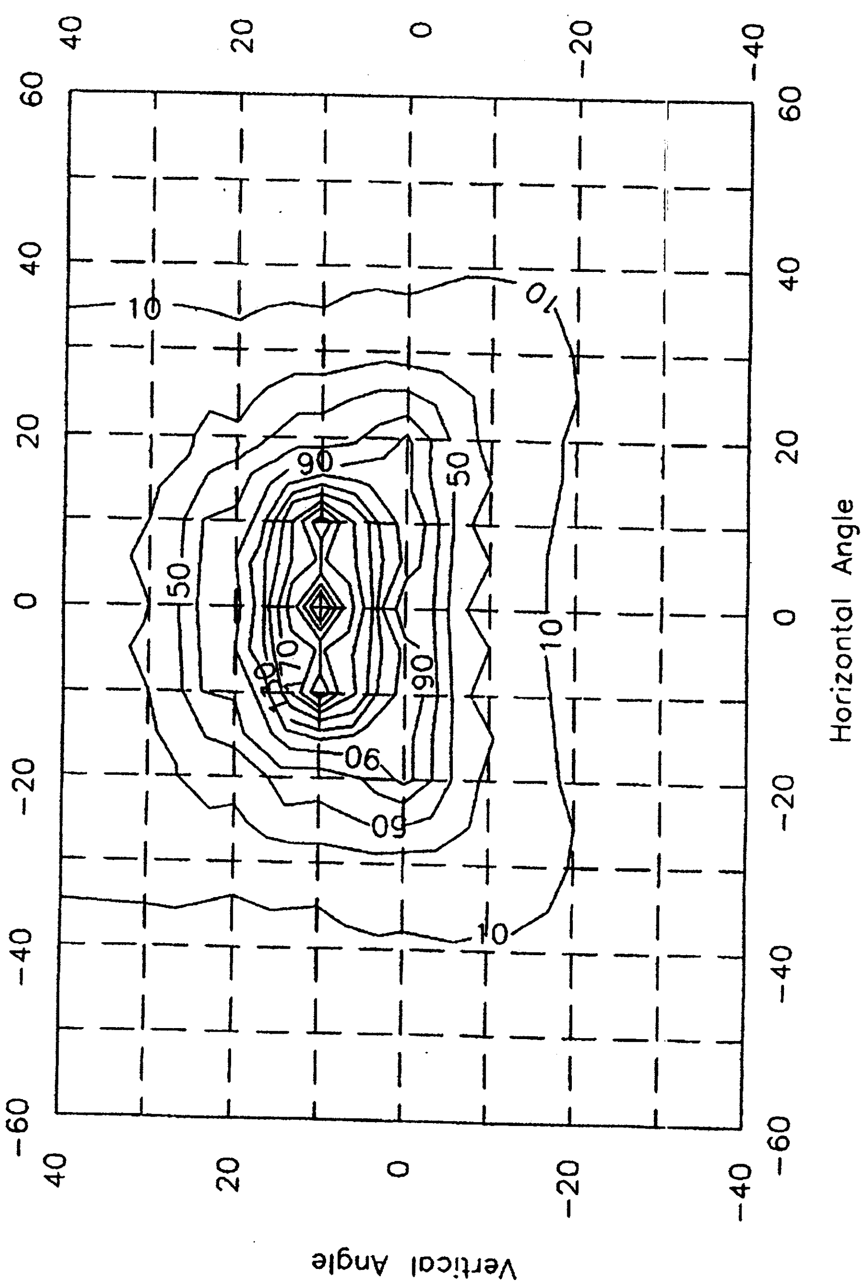


FIG. 10

Von=6.8V
R=320nm
λ=480nm

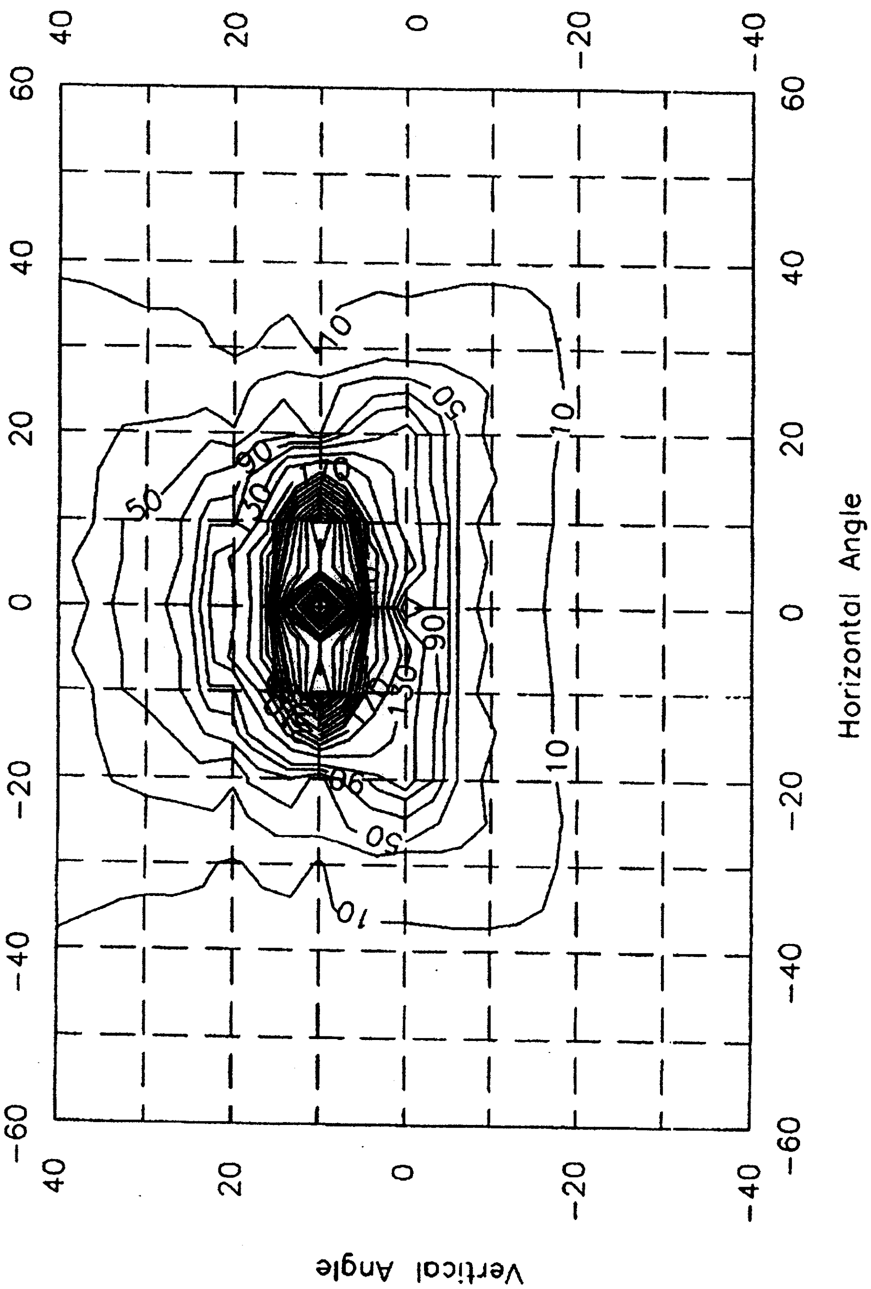
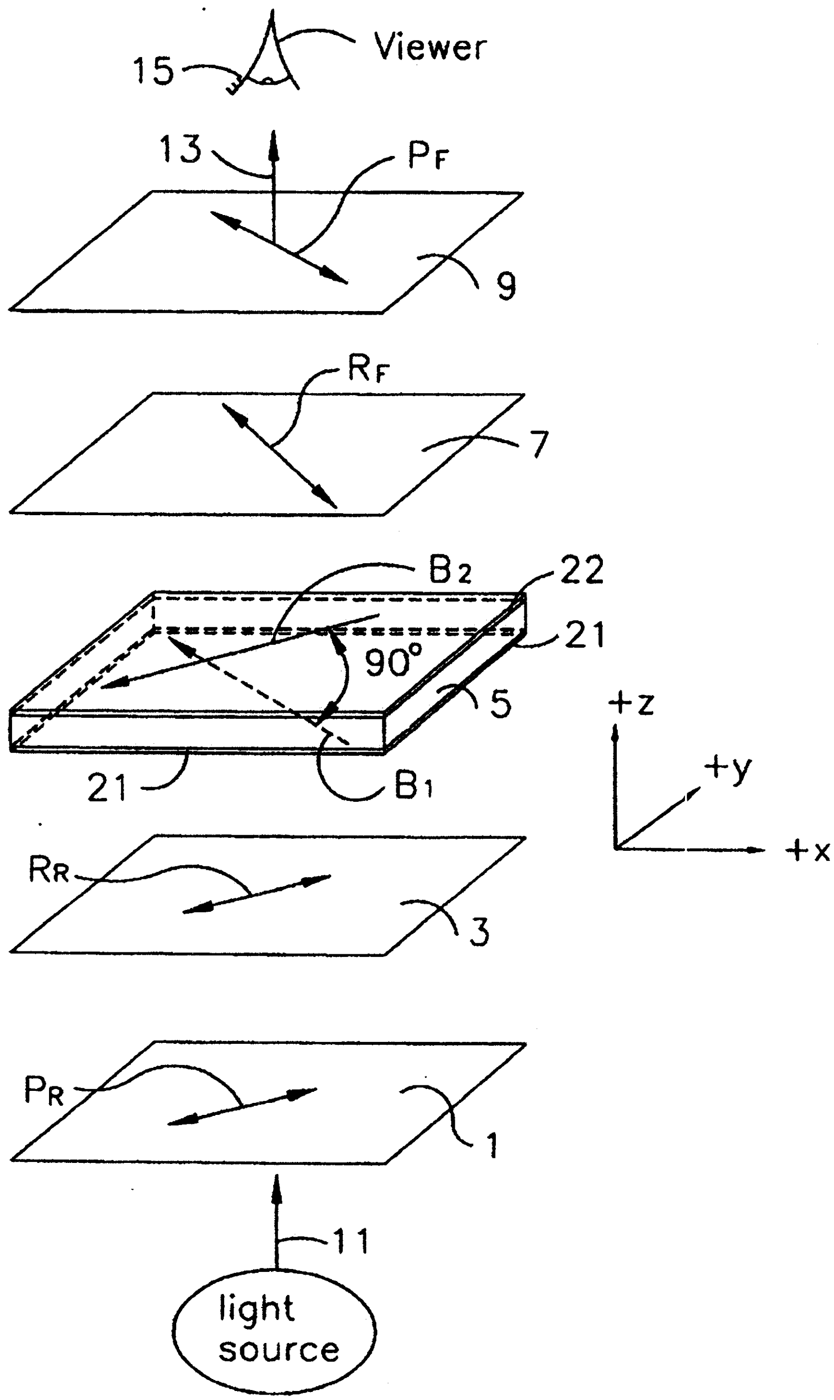


Fig. 11(a)



Viewer
15
13
PF
9
RF
7
B2
22
21
90°
5
21
B1
+z
+y
+x
RR
3
PR
1
11
light source

Fig. 11(b)

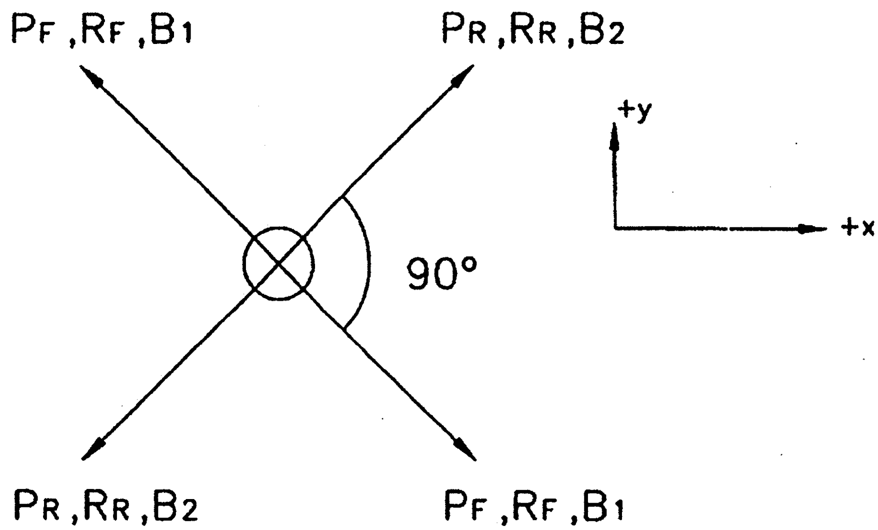


Fig. 11(c)

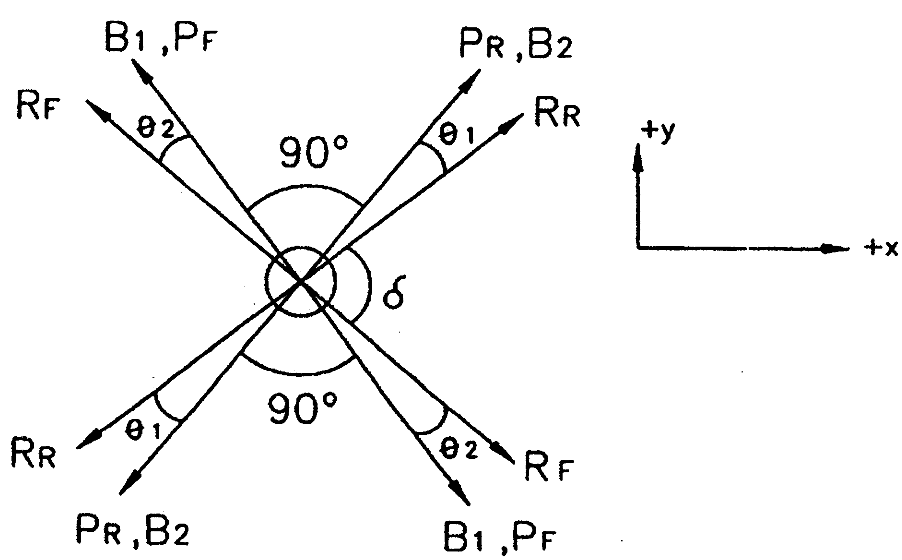
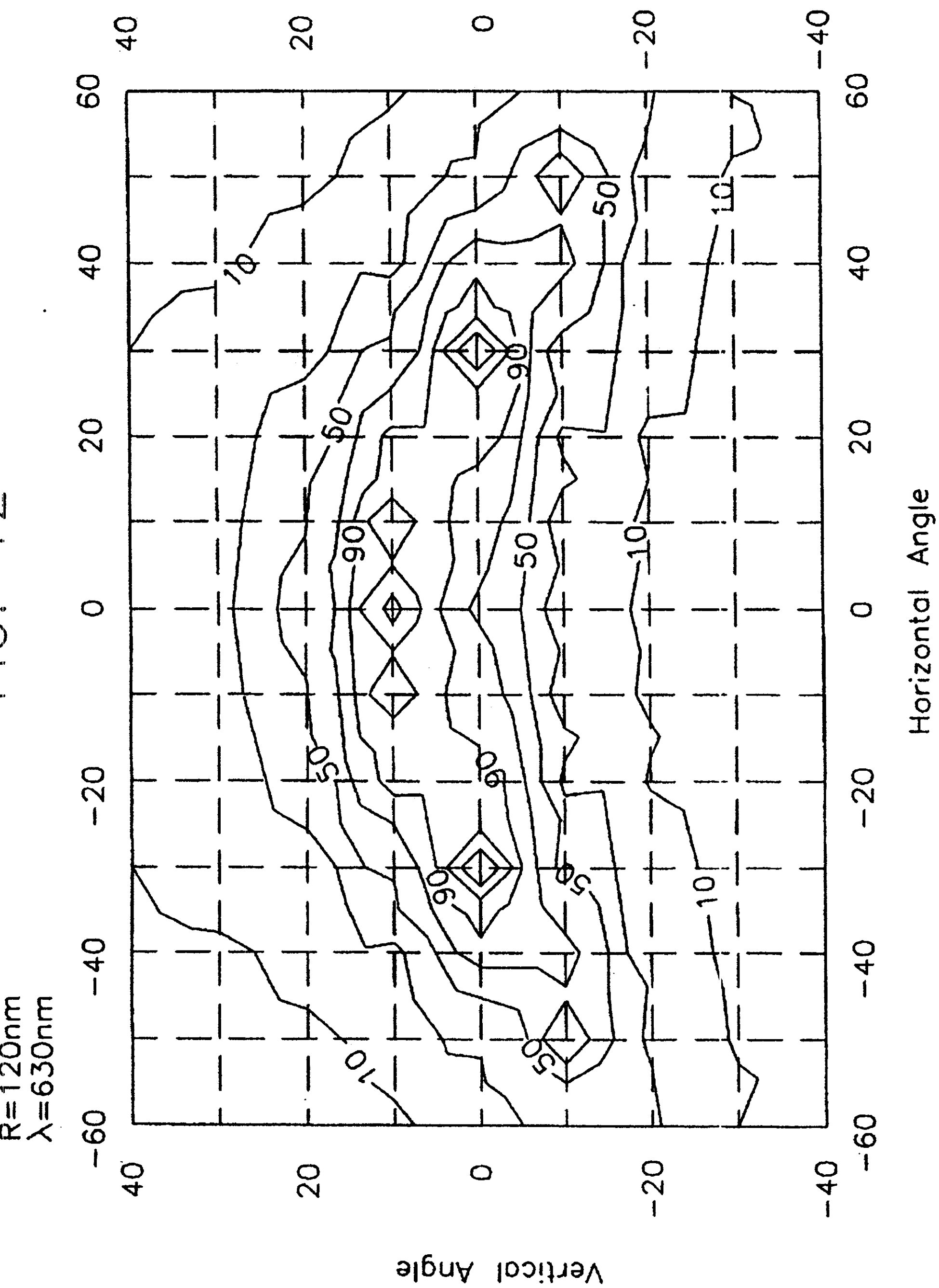


FIG. 12



Von=6.8V
R=120nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
90

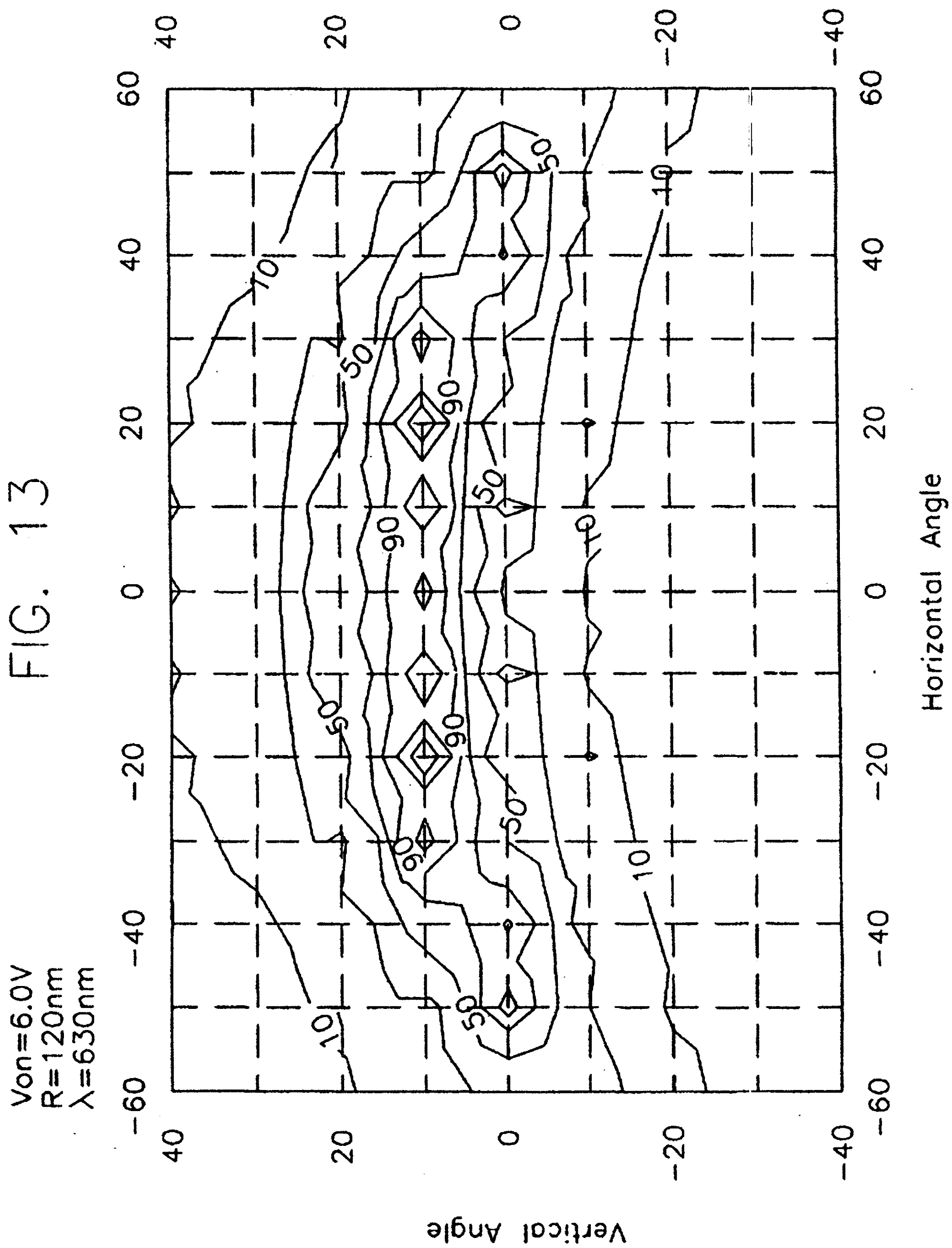
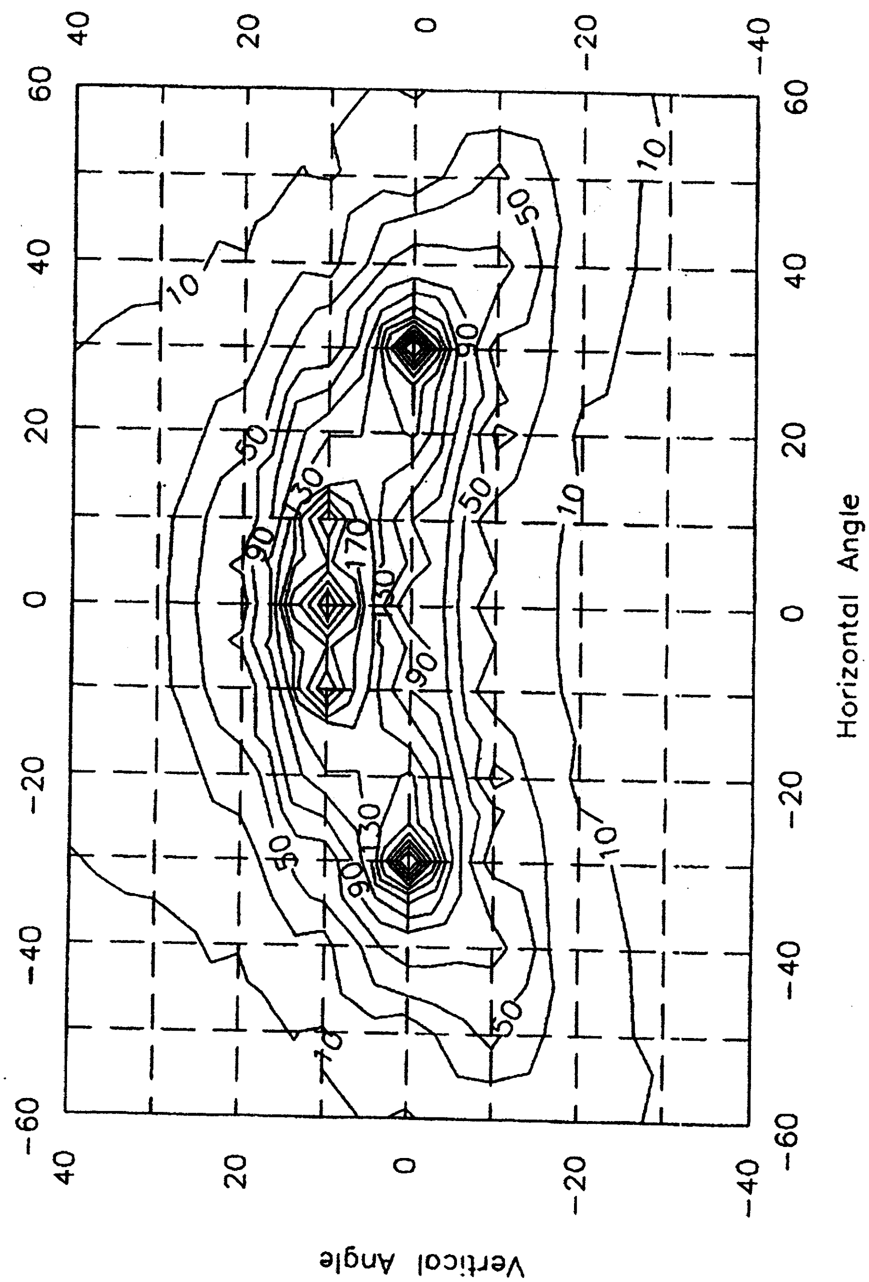

Von=6.0V
R=120nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
70
90

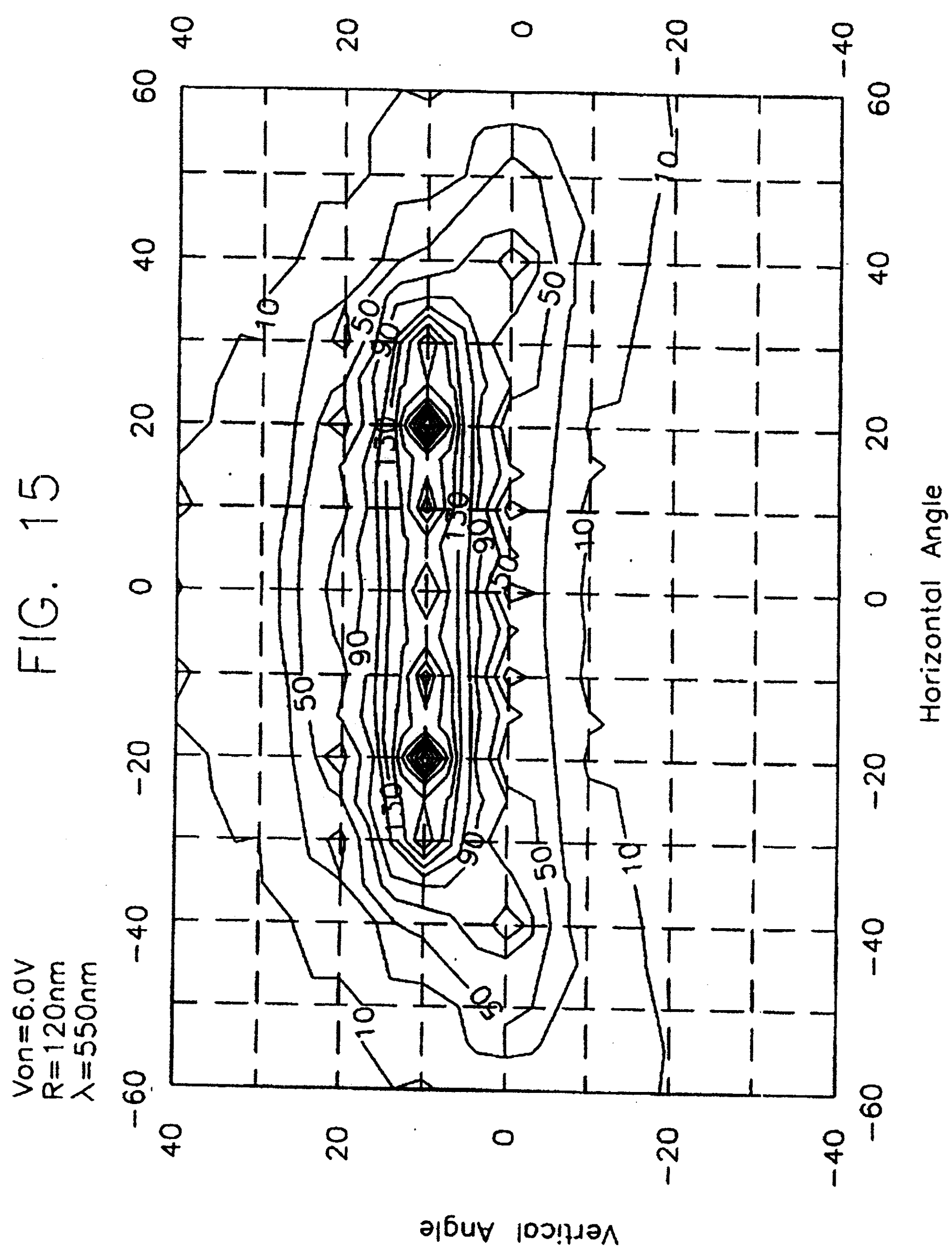
FIG. 13

FIG. 14



Von=6.8V
R=120nm
λ=550nm

FIG. 15


Von=6.0V
R=120nm
λ=550nm
Horizontal Angle
Vertical Angle
10
50
90
130
-60
-40
-20
0
20
40
60

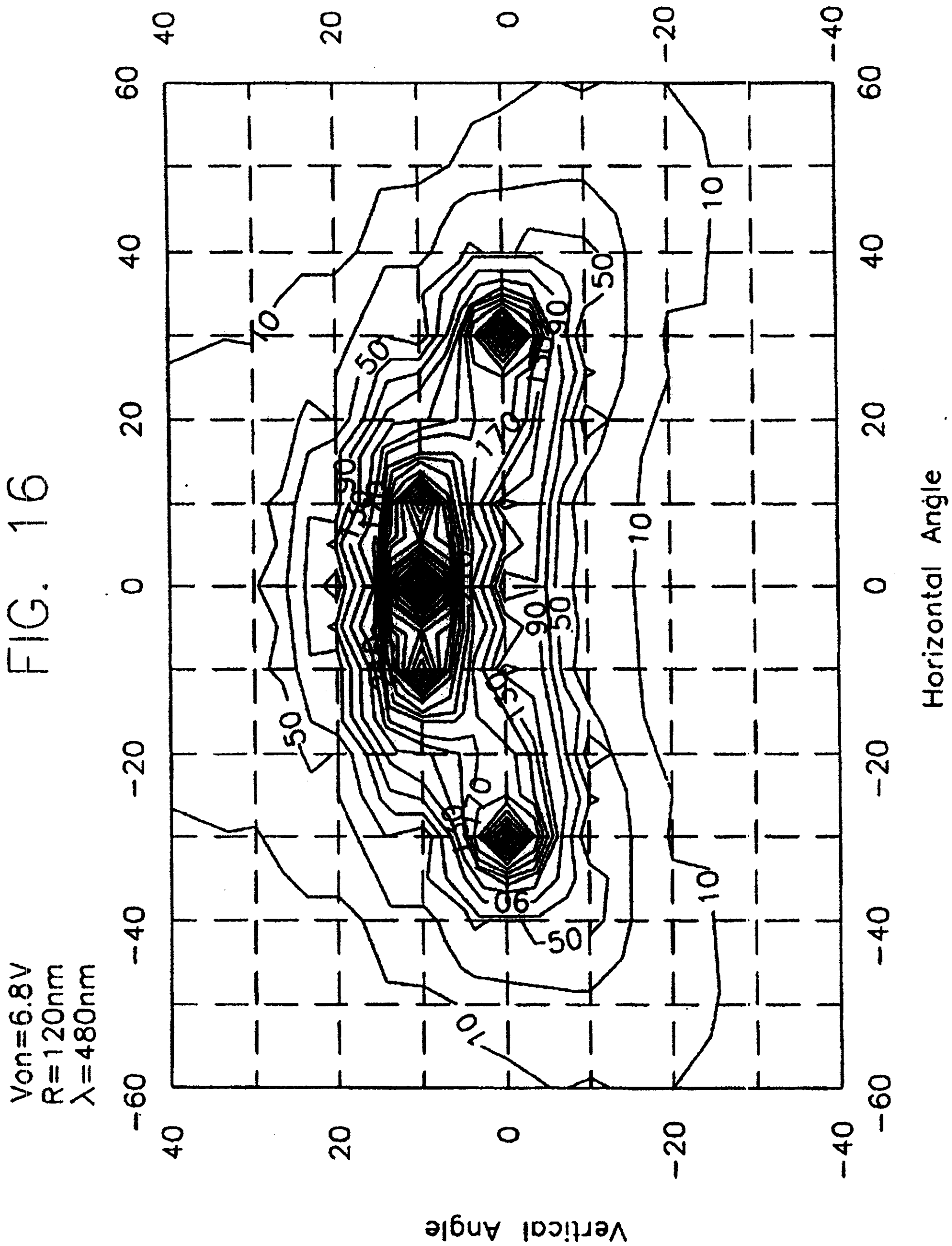


FIG. 16

FIG. 17

Von=6.0V
R=120nm
λ=480nm

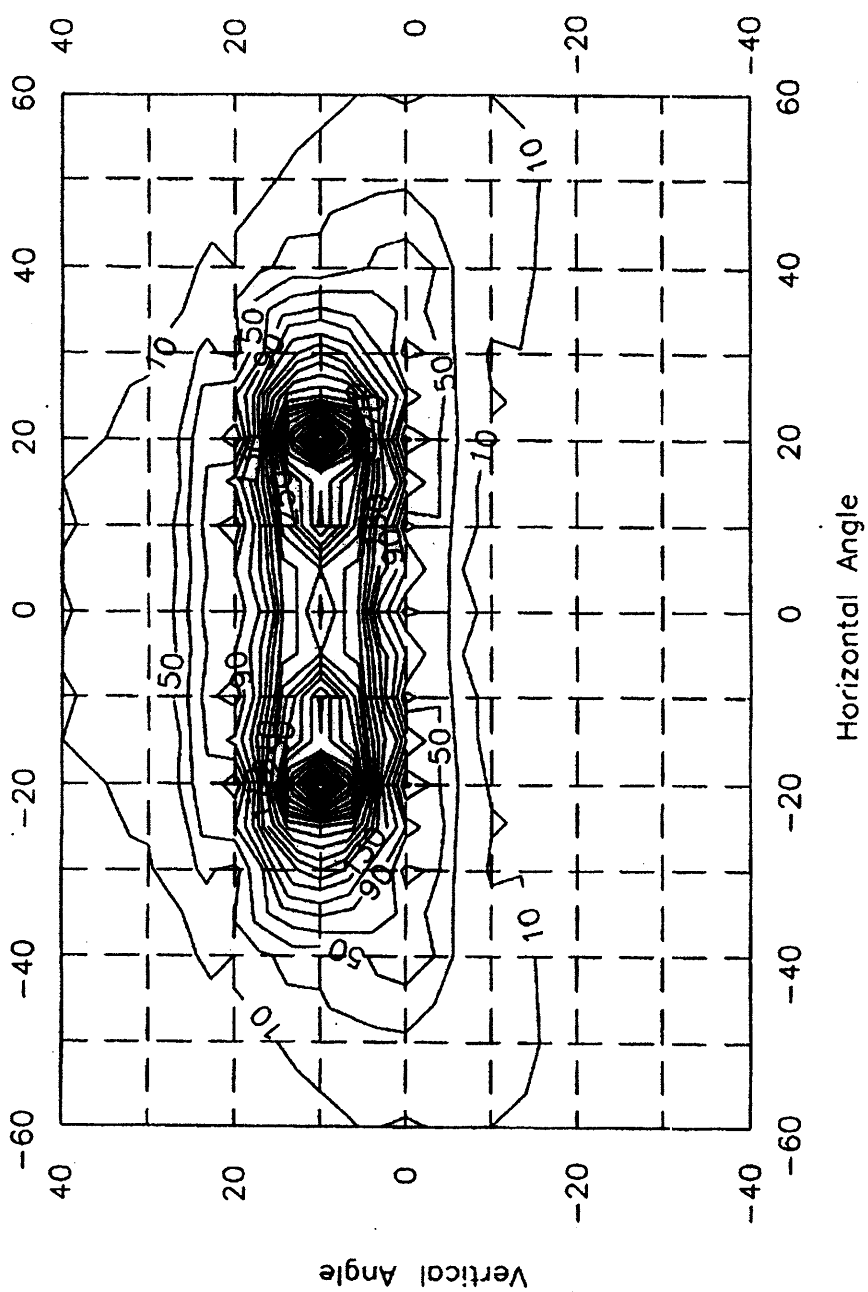


FIG. 18

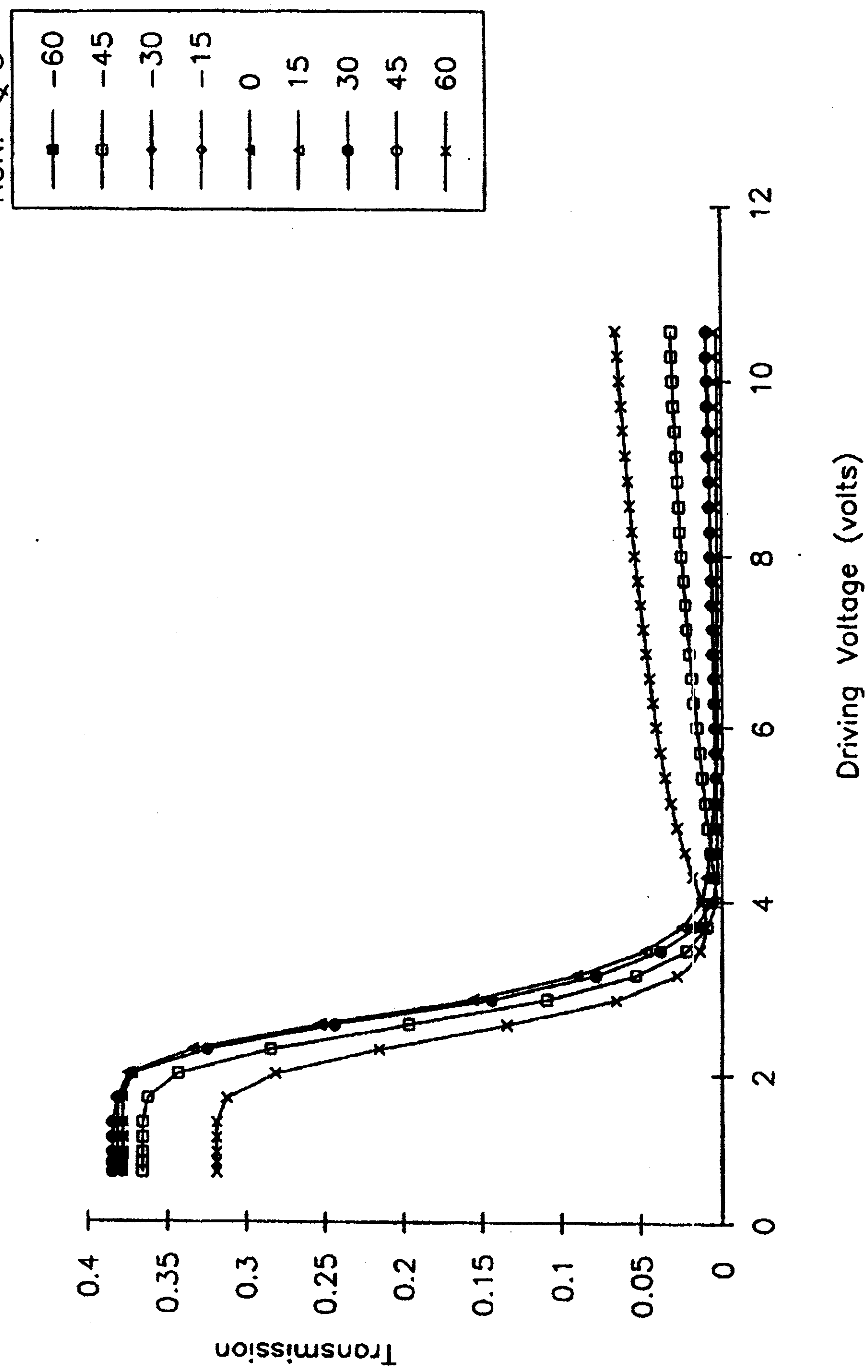

HOR. ∢'S
−60
−45
−30
−15
0
15
30
45
60
Transmission
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Driving Voltage (volts)
0
2
4
6
8
10
12

FIG. 19

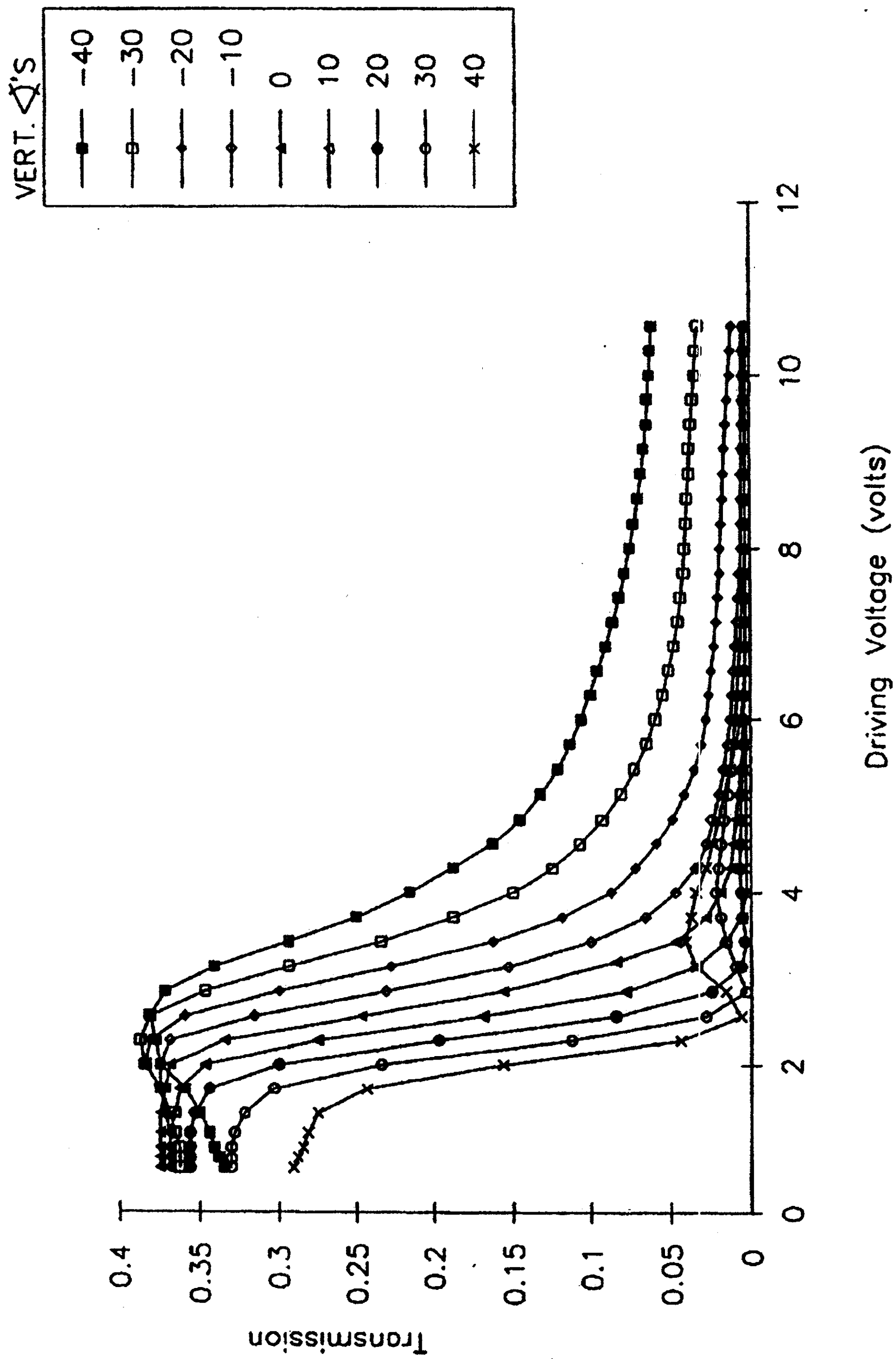

VERT. ∢'S
−40
−30
−20
−10
0
10
20
30
40
Transmission
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Driving Voltage (volts)
0
2
4
6
8
10
12

FIG. 20

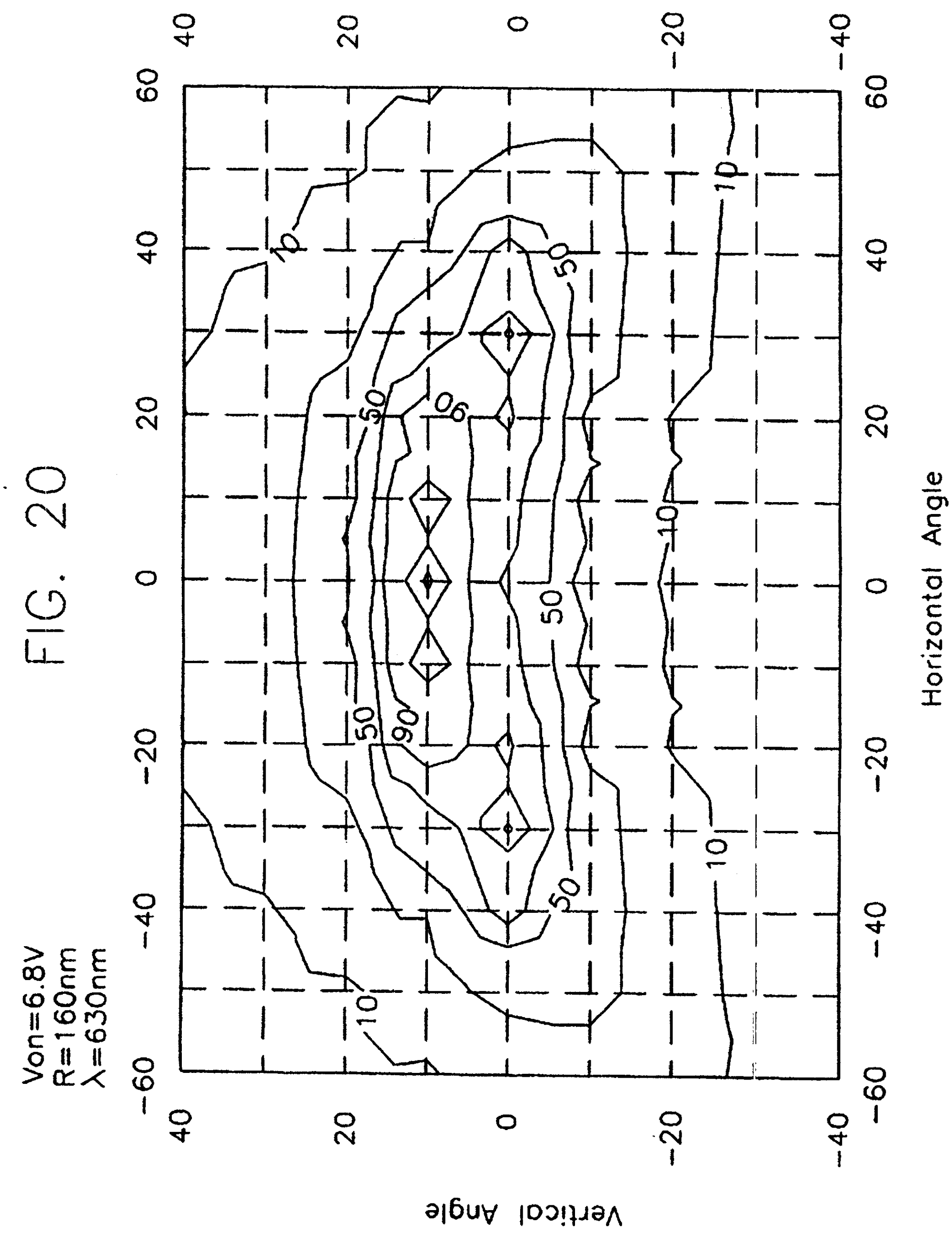

Von=6.8V
R=160nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
90

FIG. 21

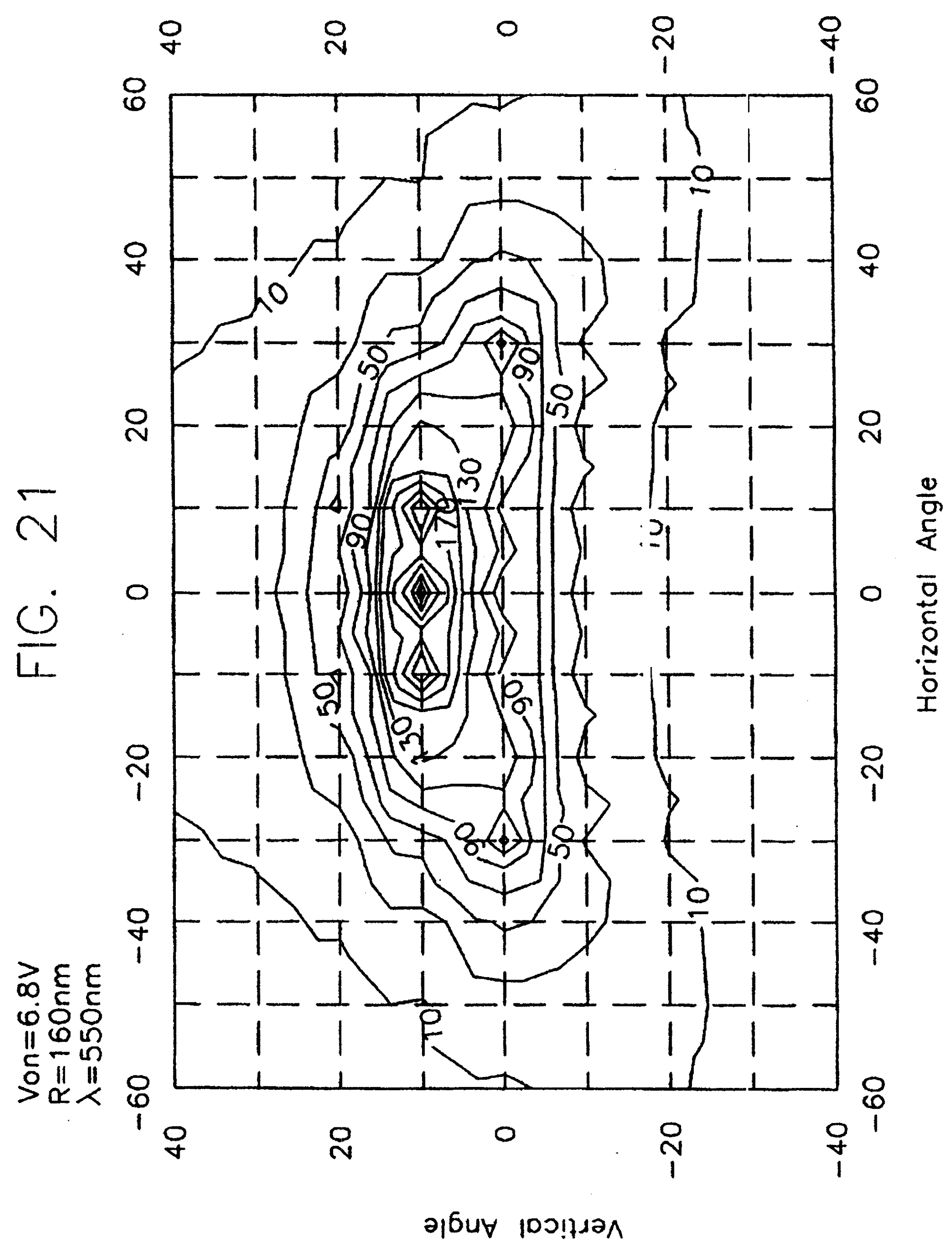

Von=6.8V
R=160nm
λ=550nm
Horizontal Angle
Vertical Angle
10
50
90
130
170

FIG. 22

Von=6.8V
R=160nm
λ=480nm

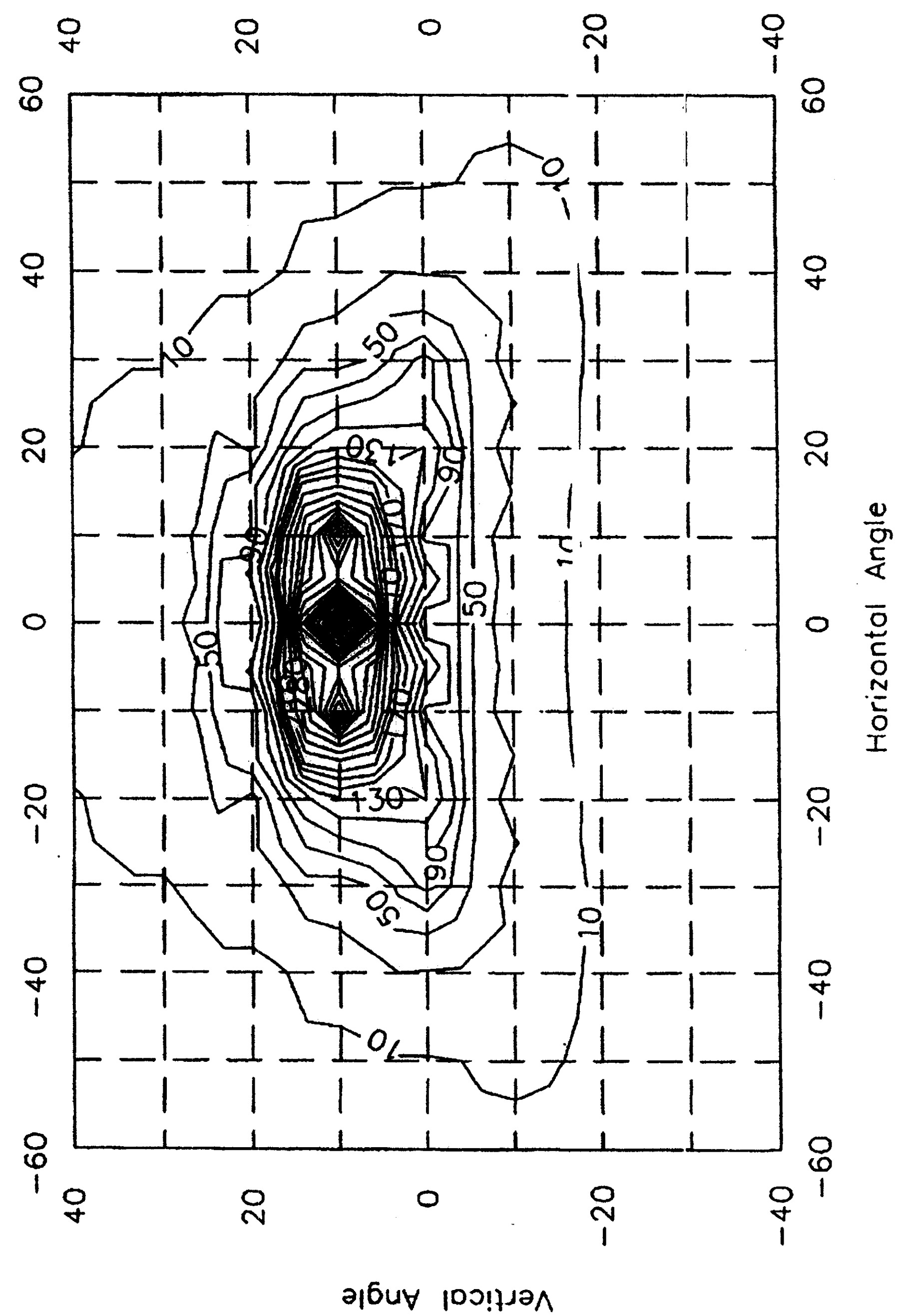
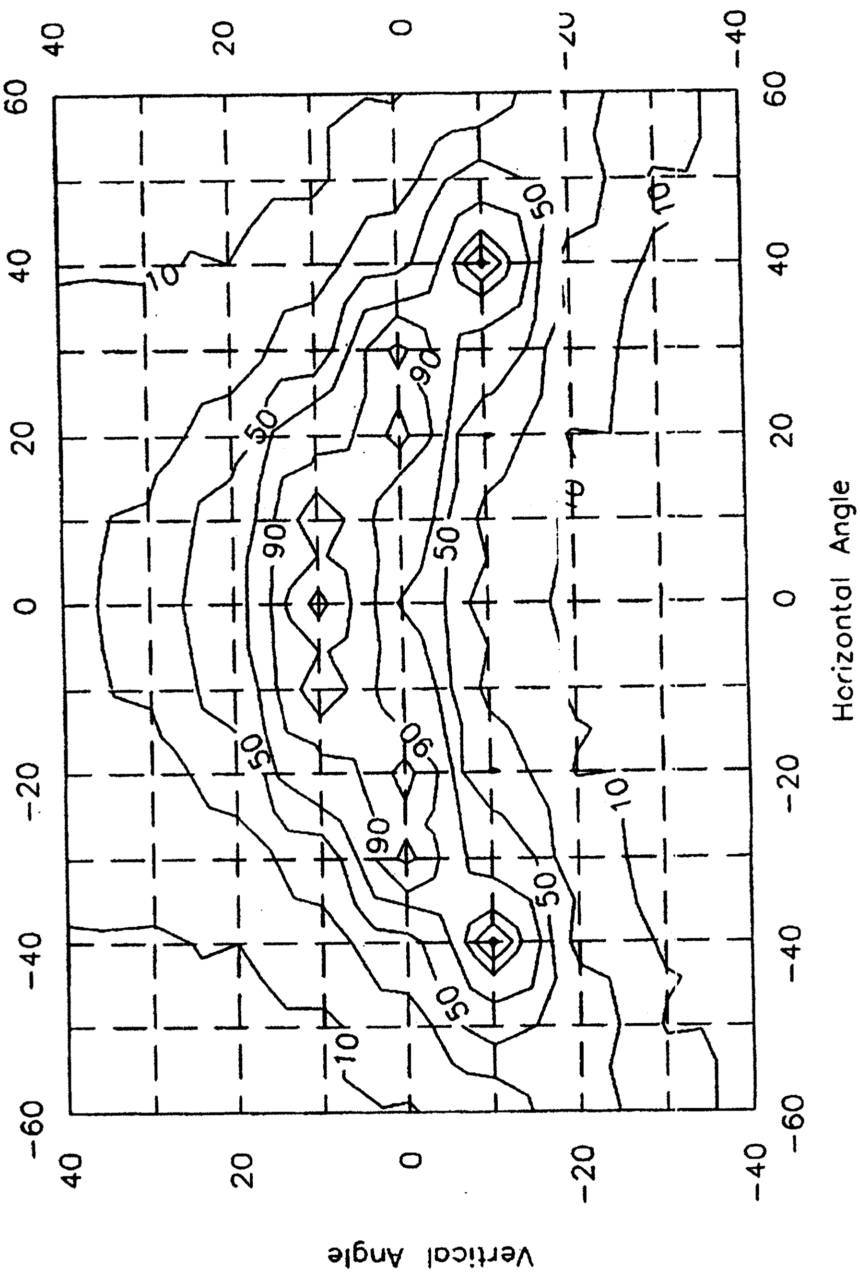


FIG. 23



Von=6.8V
R=80nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
90

FIG. 24

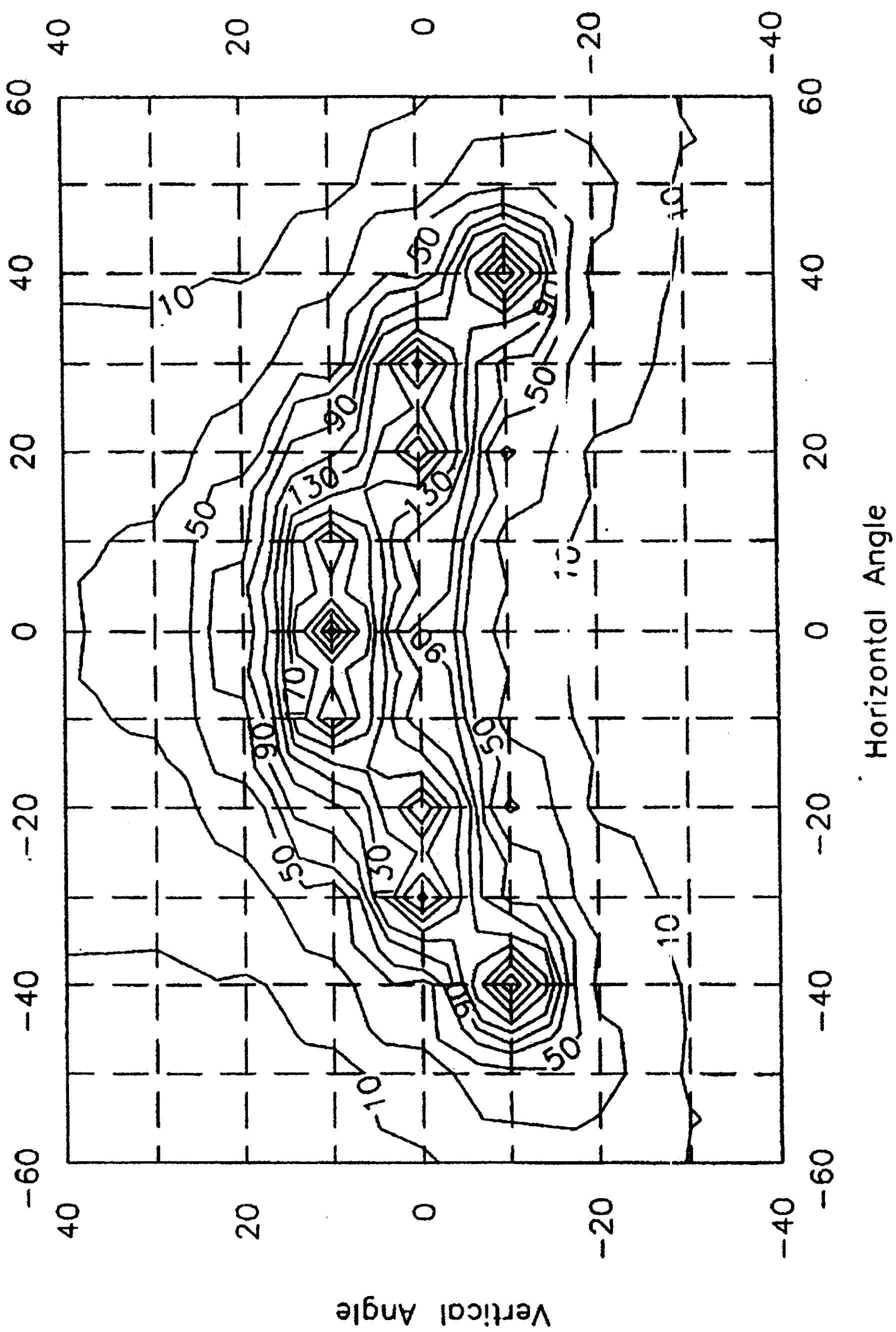
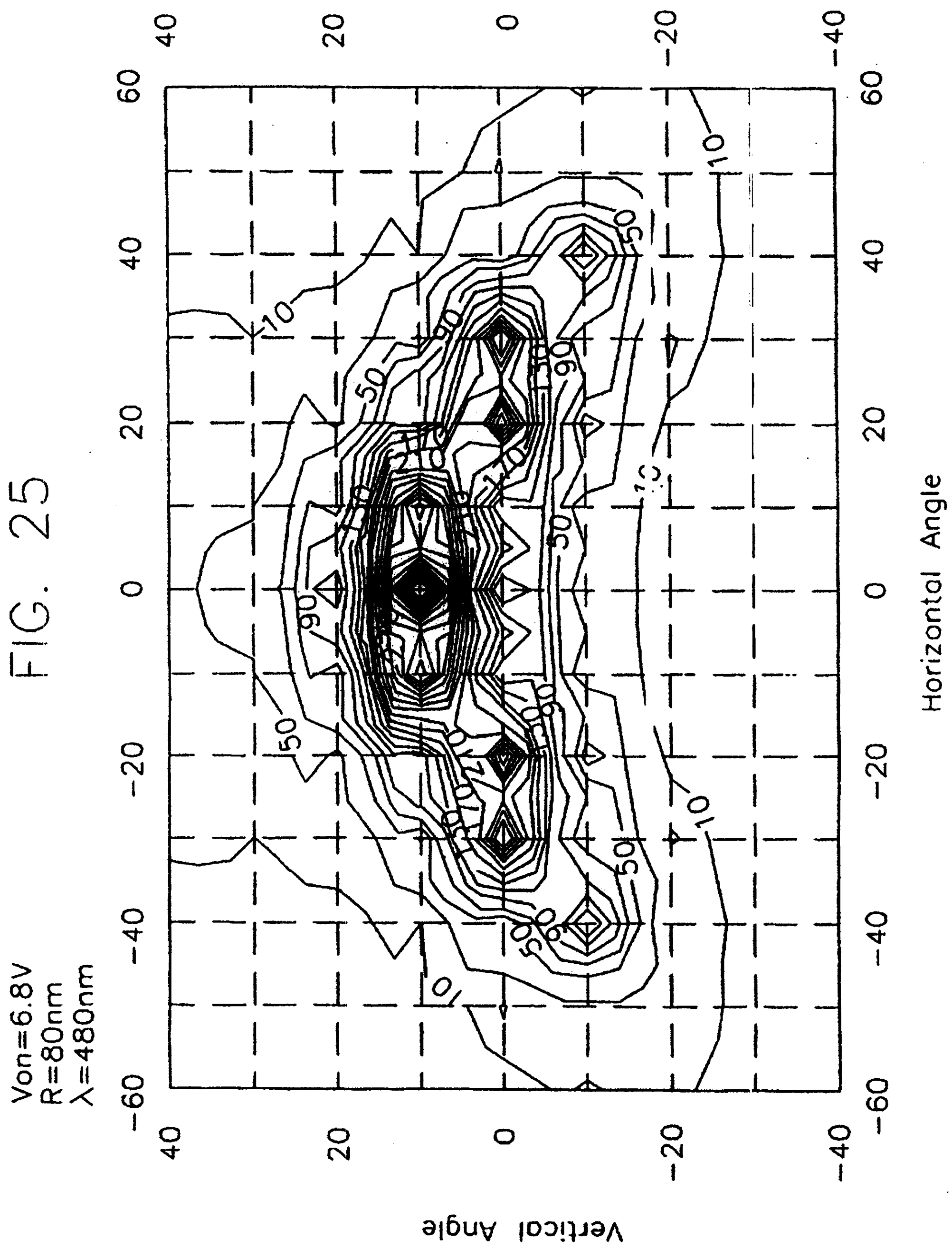

Von=6.8V
R=80nm
λ=550nm
Horizontal Angle
Vertical Angle
10
50
90
130

FIG. 25



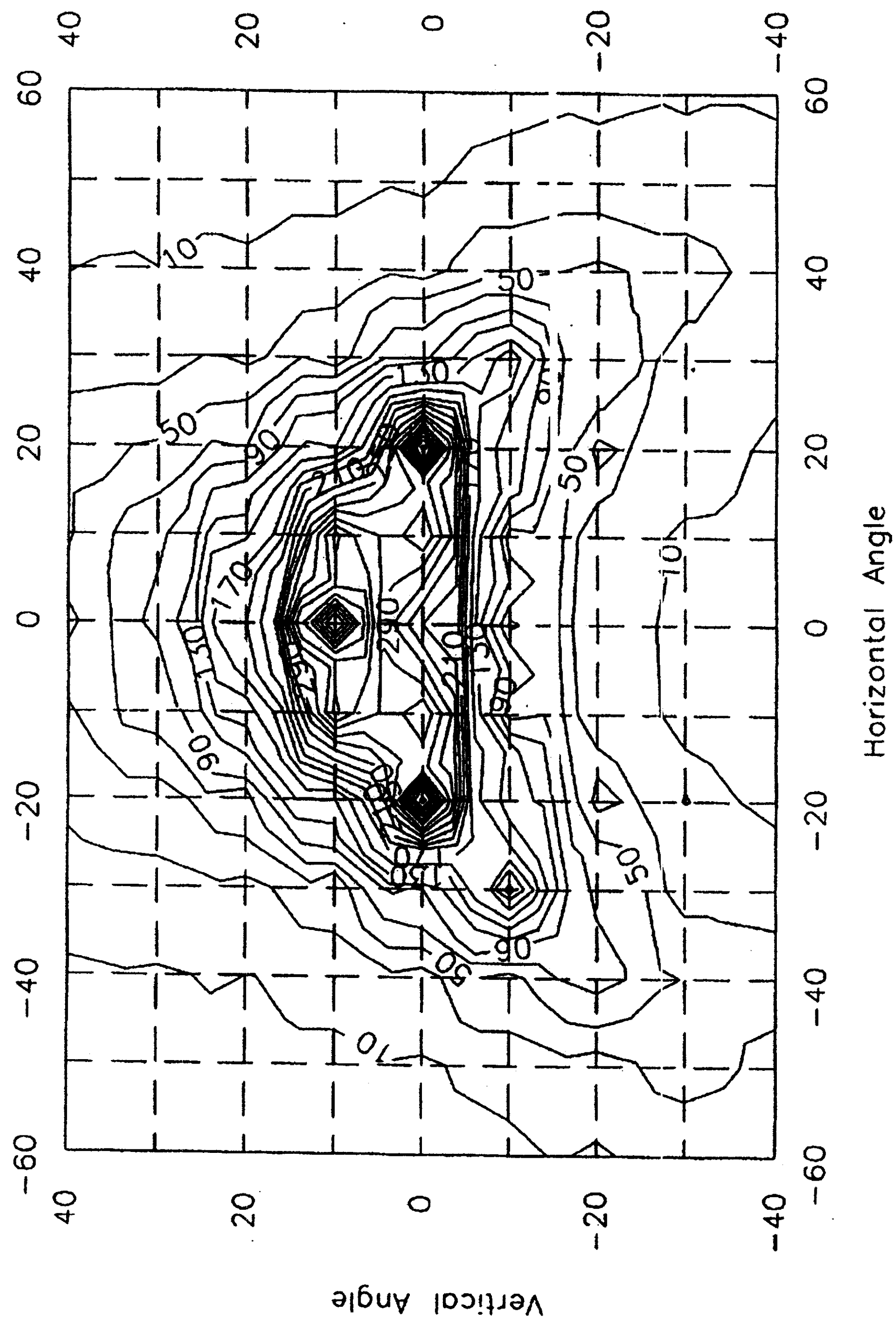


FIG. 26

Von=6.8V
R=120nm
λ=WHITE

FIG. 27

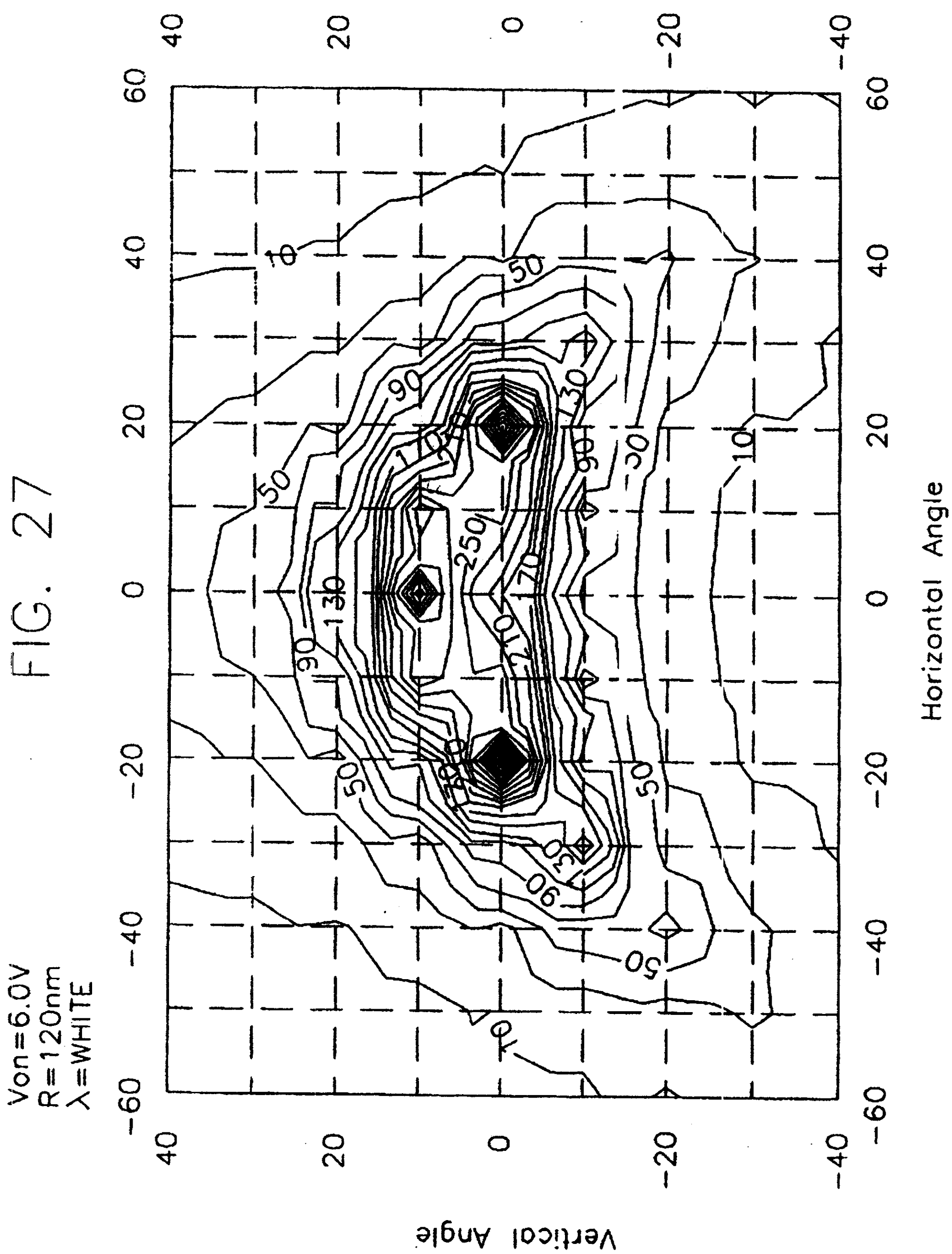

Von=6.0V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
10
50
90
130
170
210
250
60
40
20
0
-20
-40
-60

FIG. 28

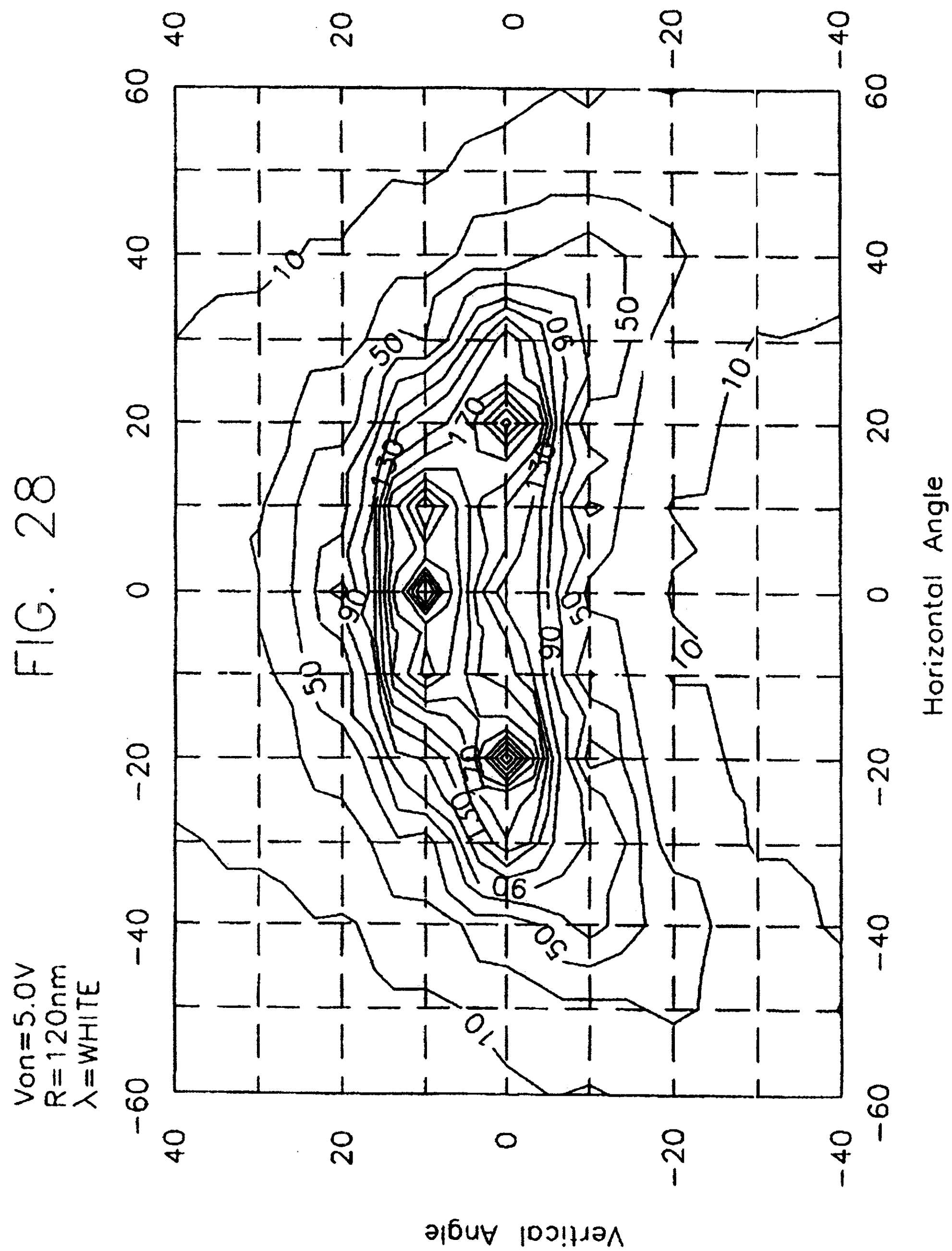


FIG. 29

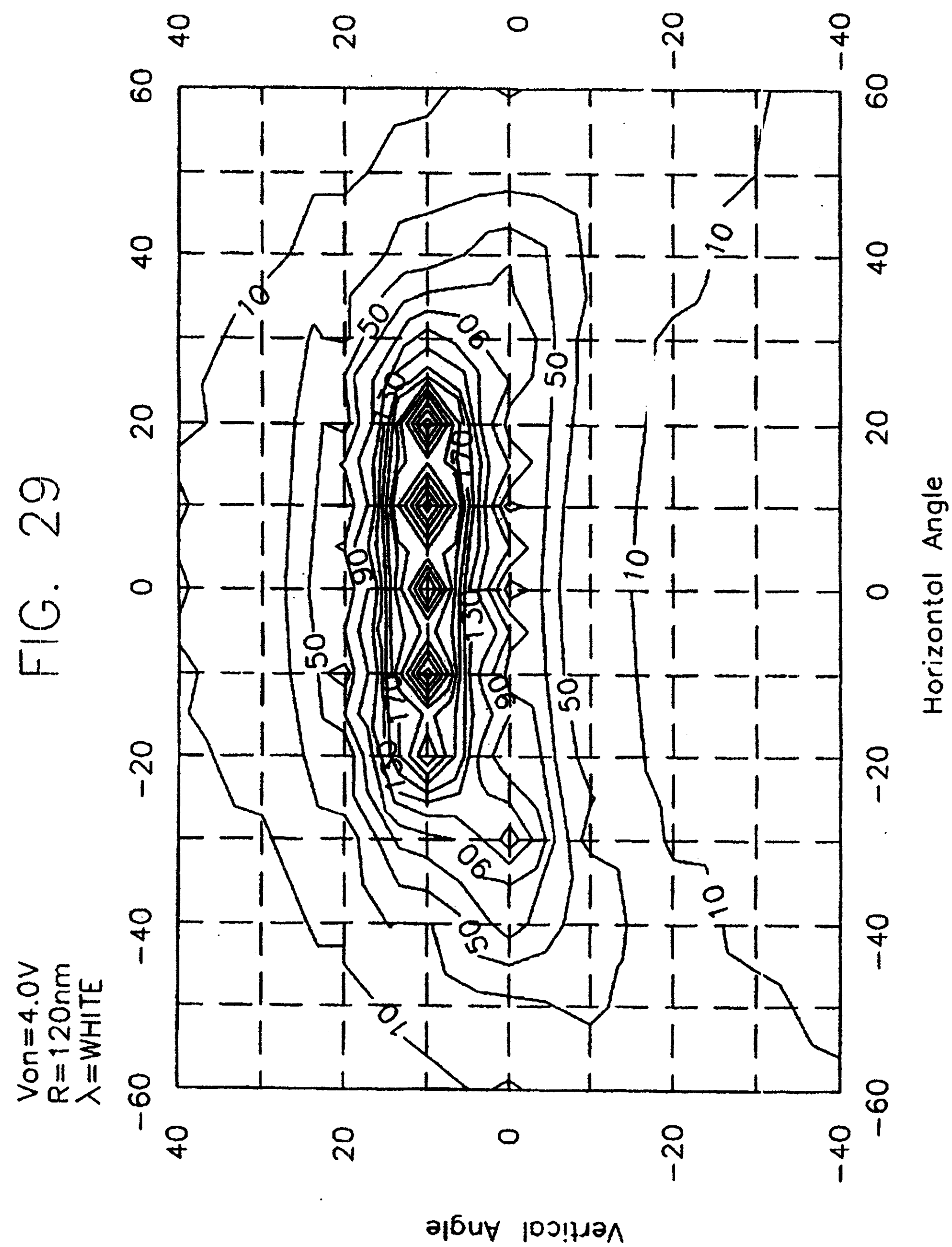

Von=4.0V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
10
50
90
130
170

FIG. 30

R=120nm
λ=White

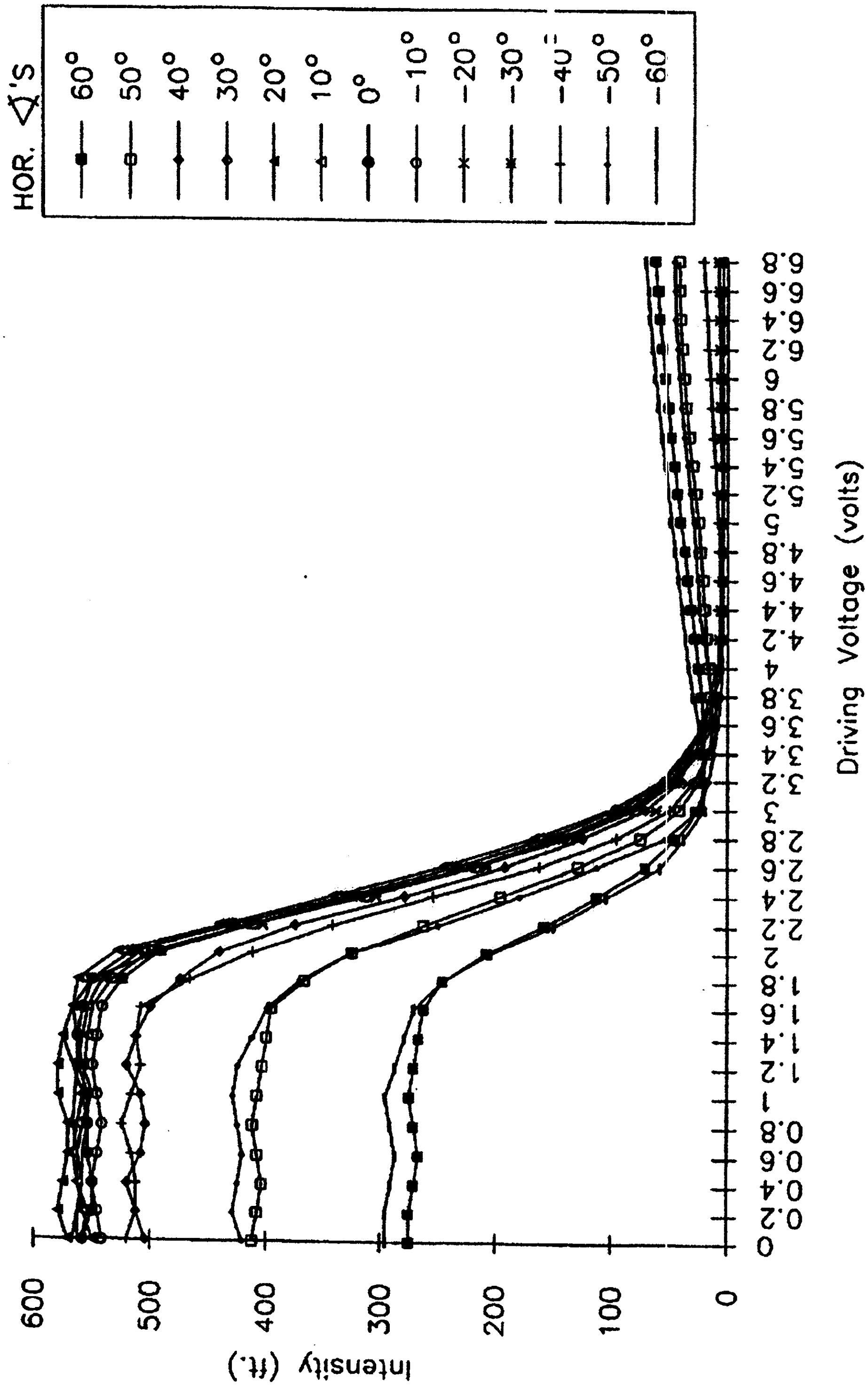


FIG. 31

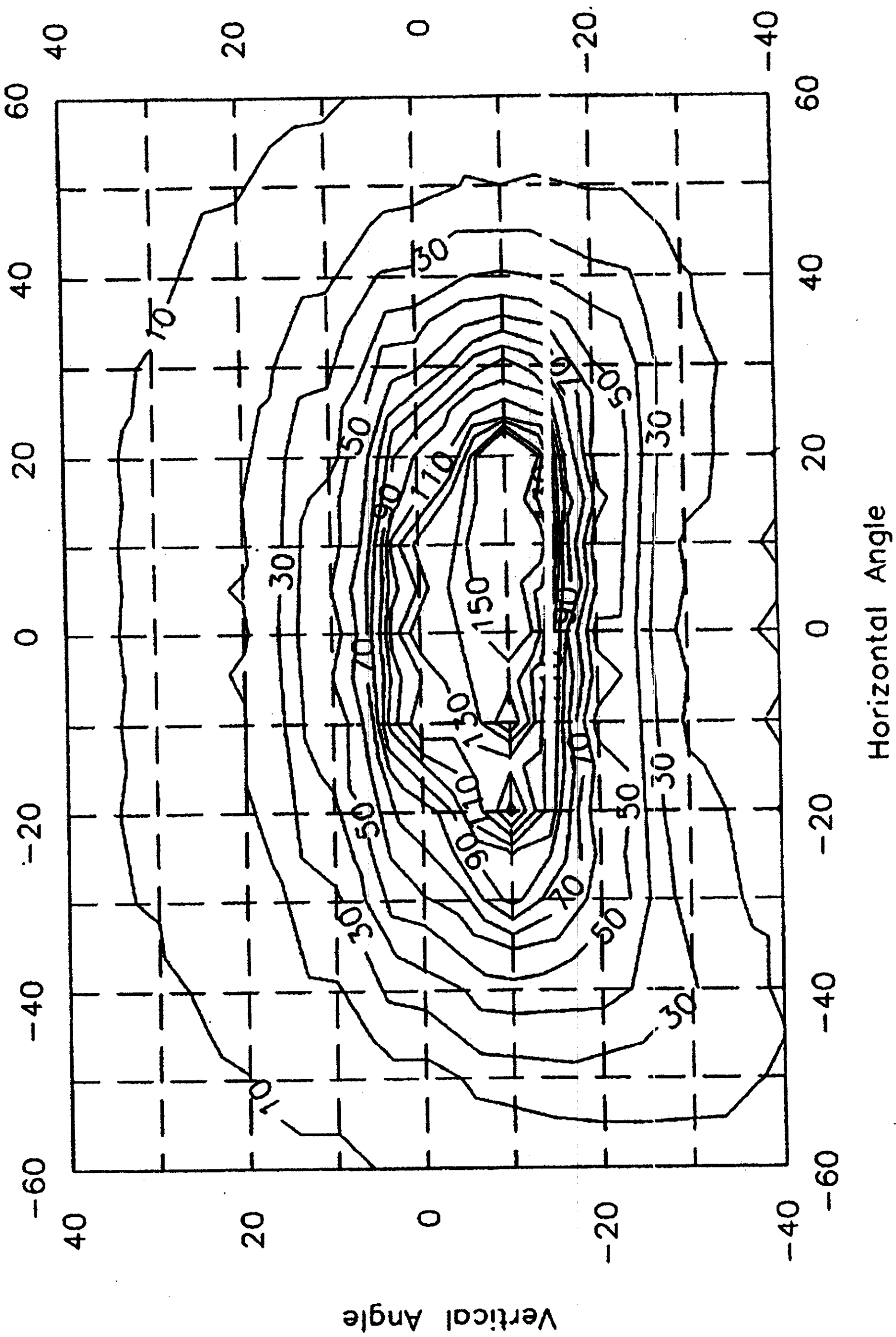


FIG. 32

Von=6.0V
R=120nm
λ=WHITE

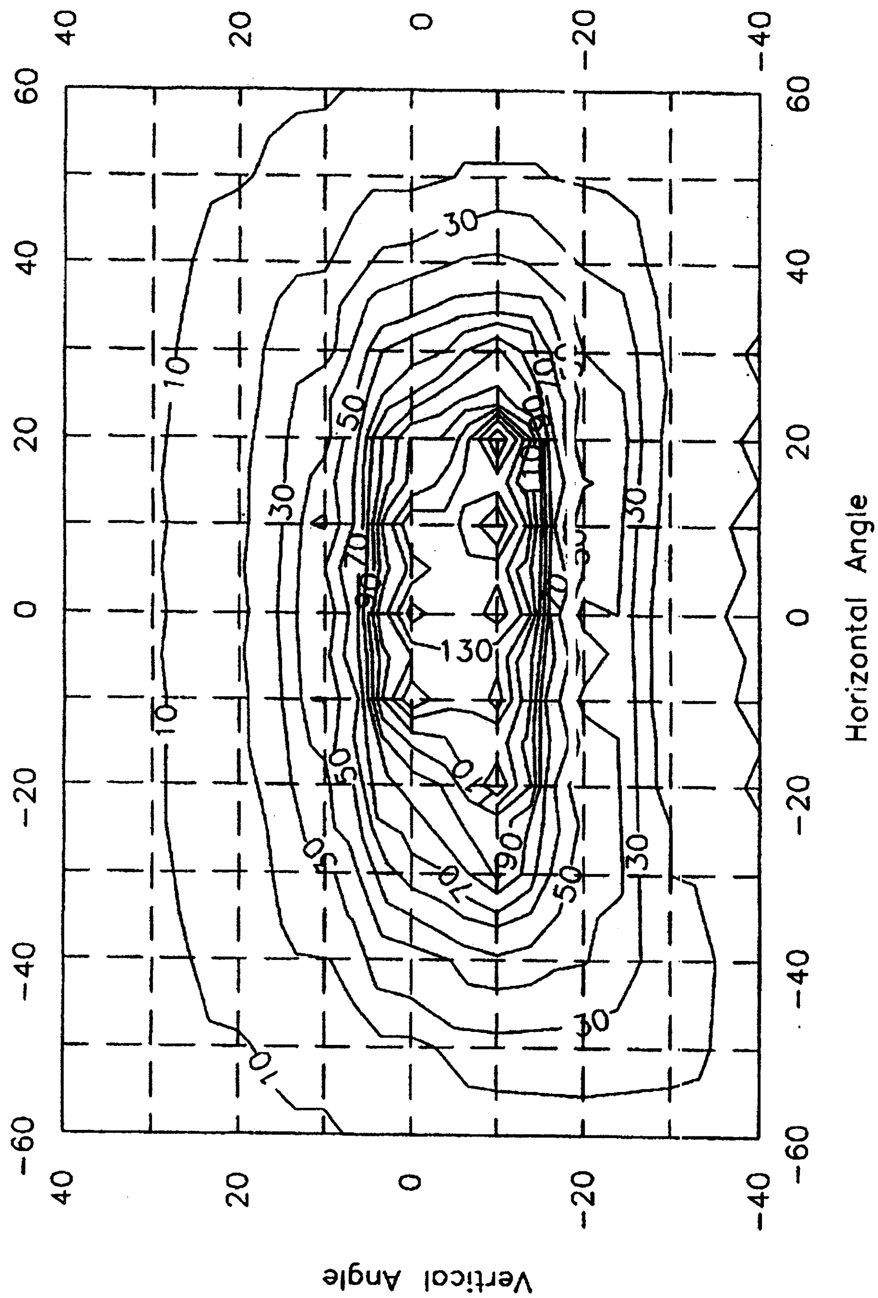


FIG. 33

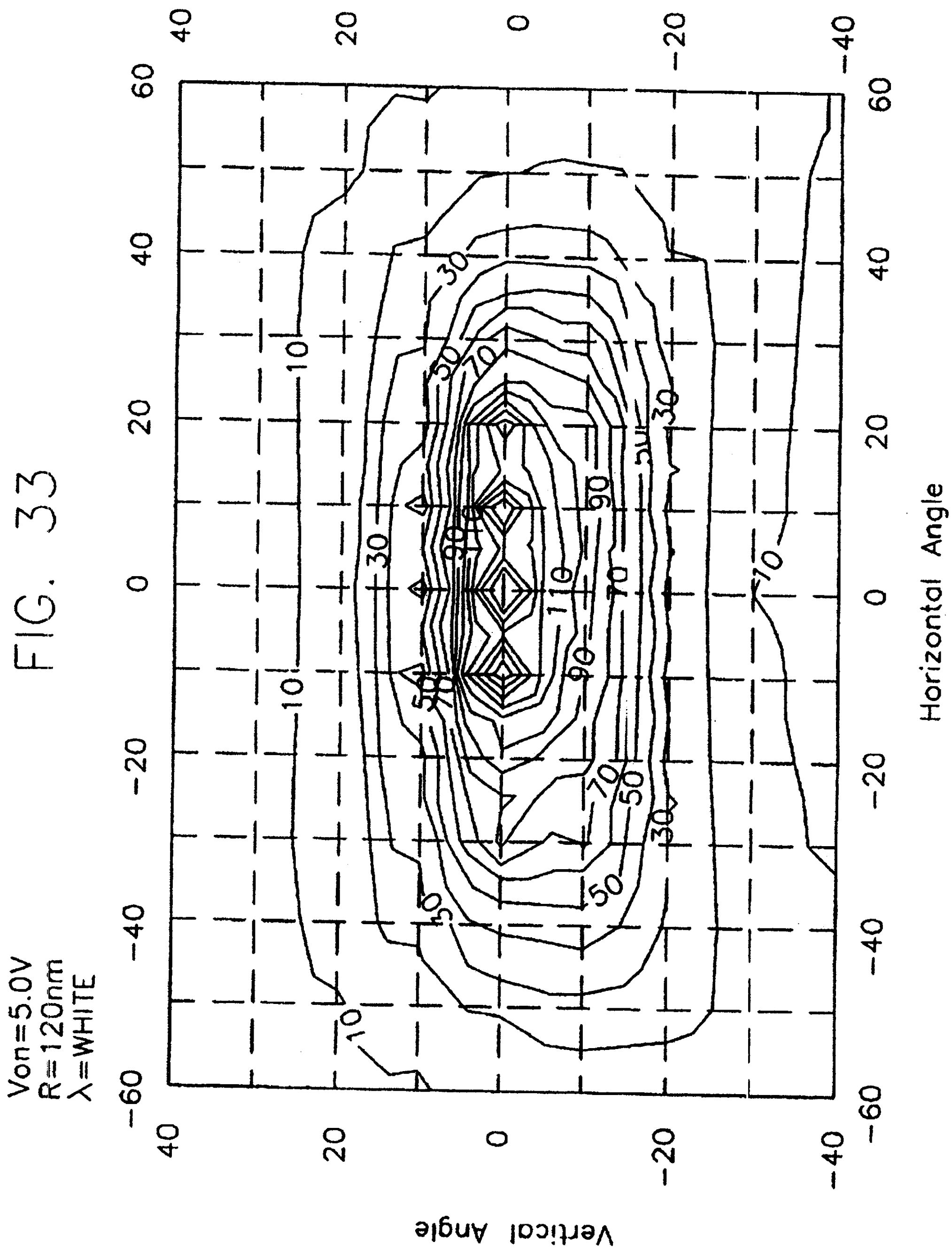


FIG. 34

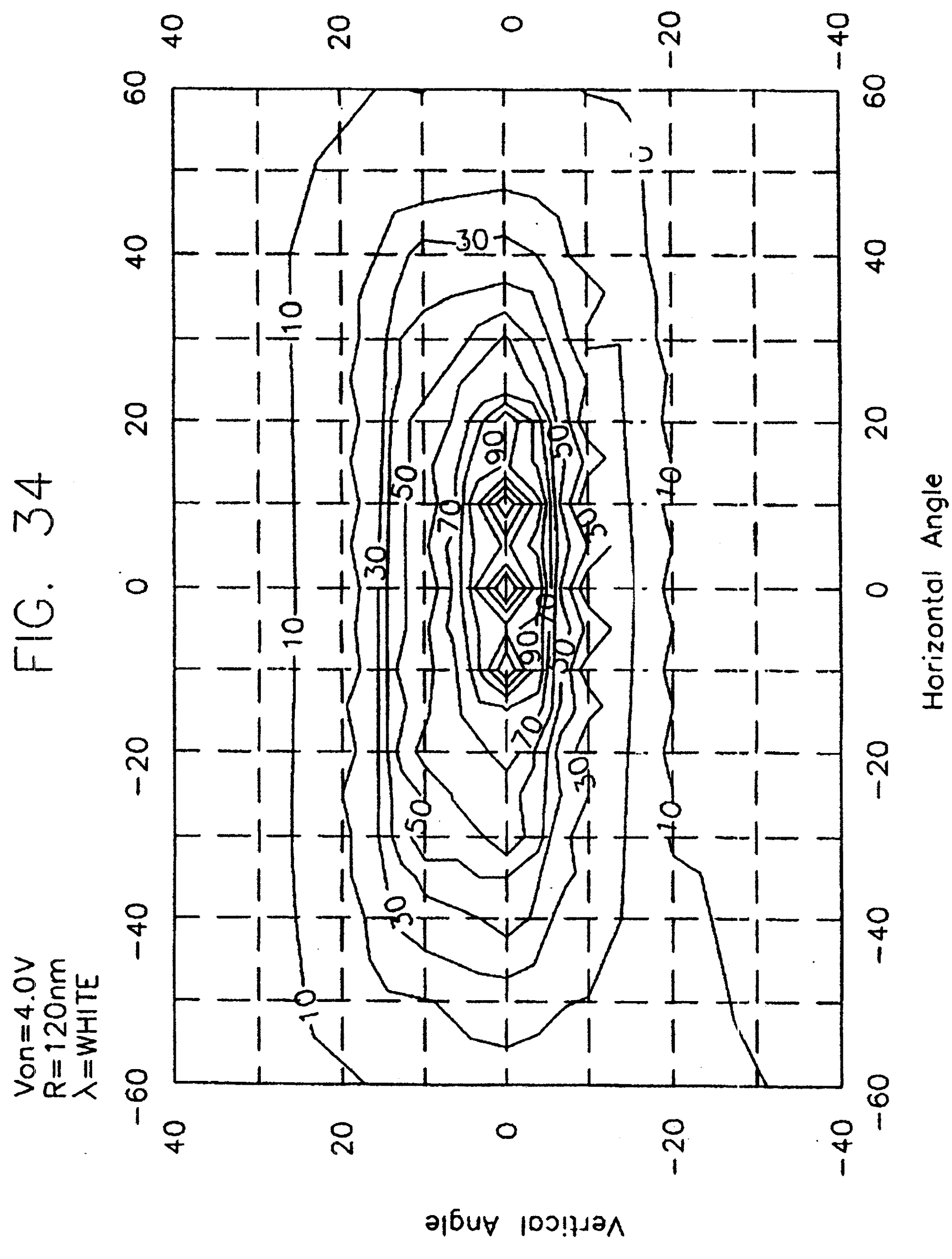

Von=4.0V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
60
40
20
0
−20
−40
−60
10
30
50
70
90

FIG. 35

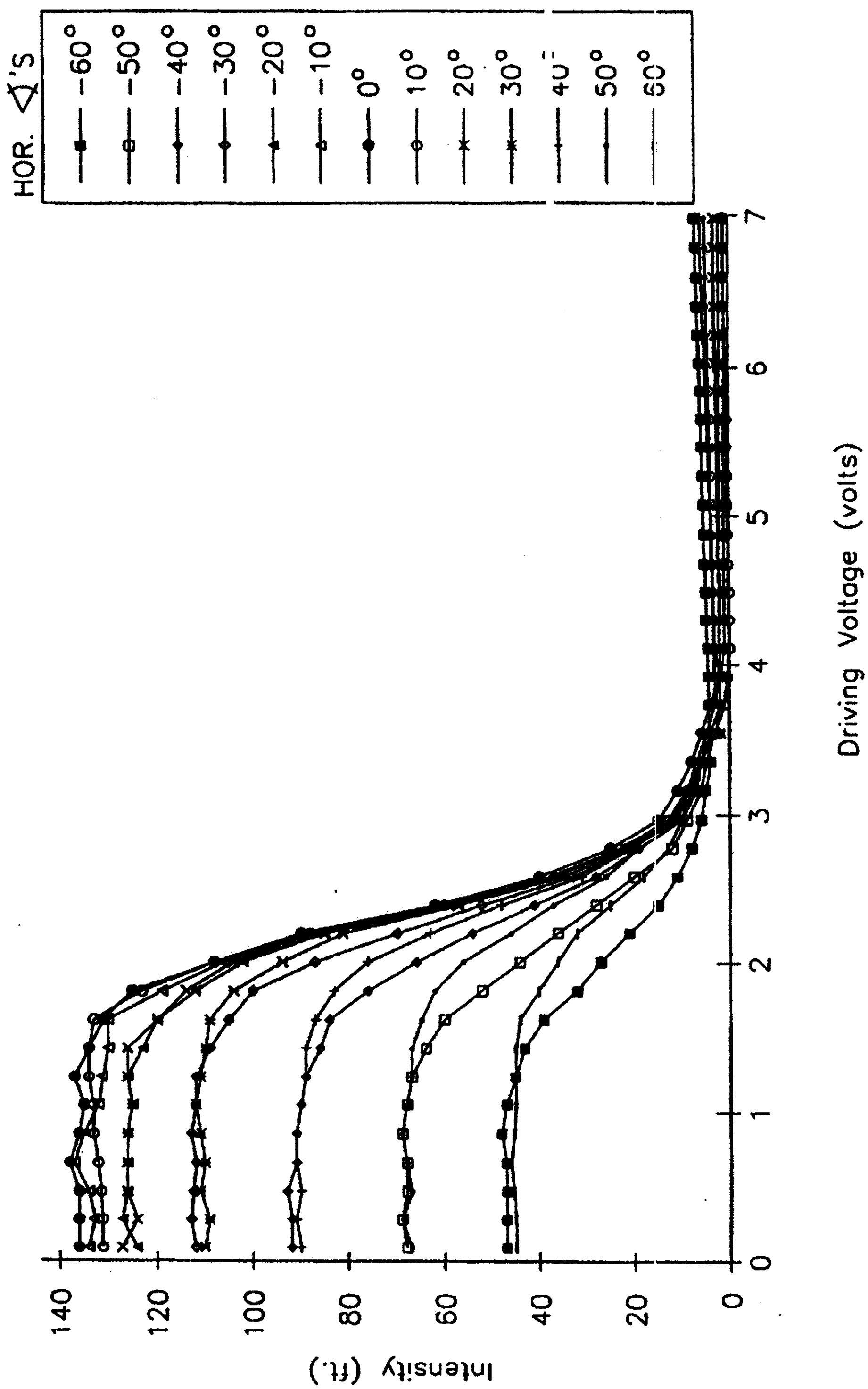

R=120nm
λ =White
HOR. ∢'S
−60°
−50°
−40°
−30°
−20°
−10°
0°
10°
20°
30°
40°
50°
60°
Intensity (ft.)
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
Driving Voltage (volts)

FIG. 36

Von=6.0V
R=120nm
λ=WHITE

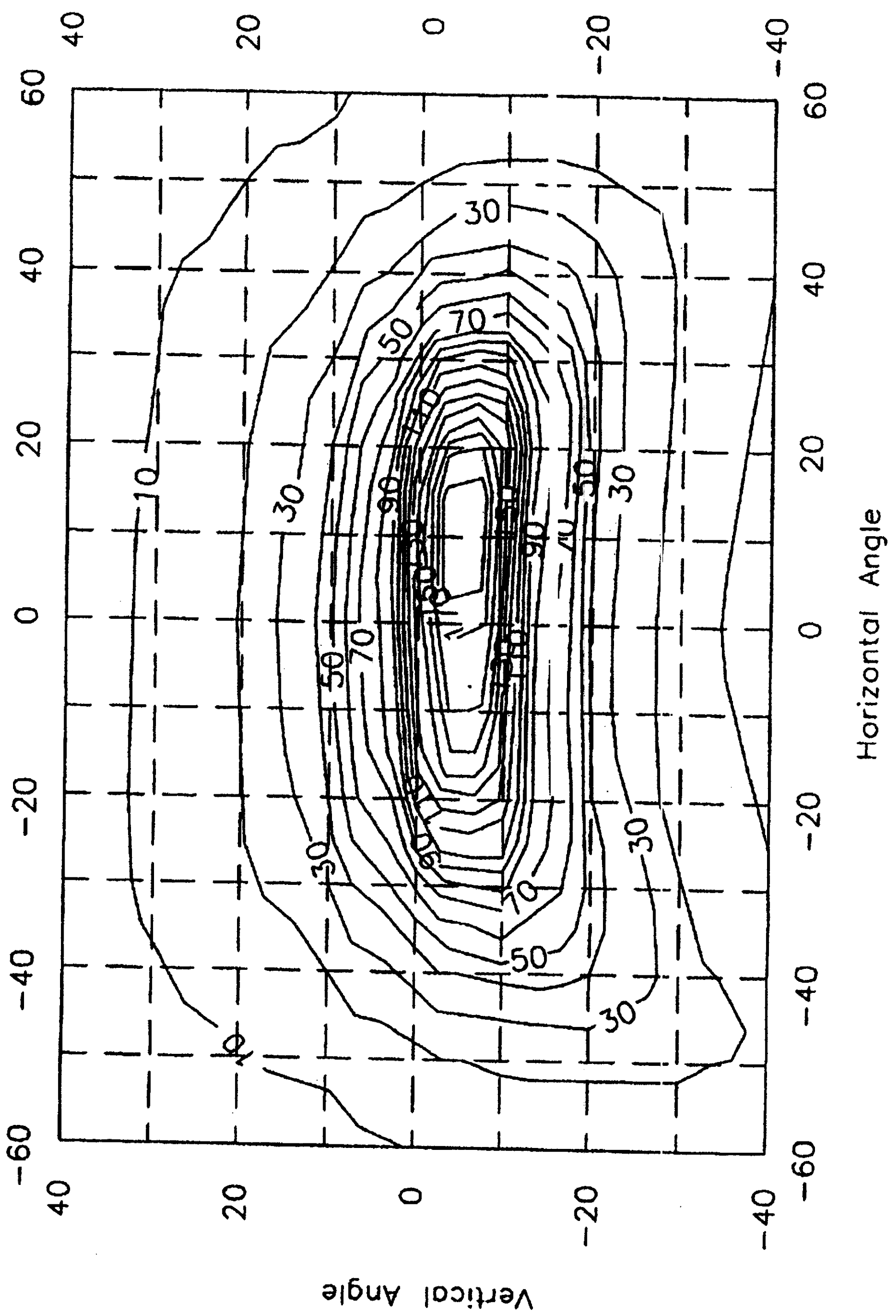
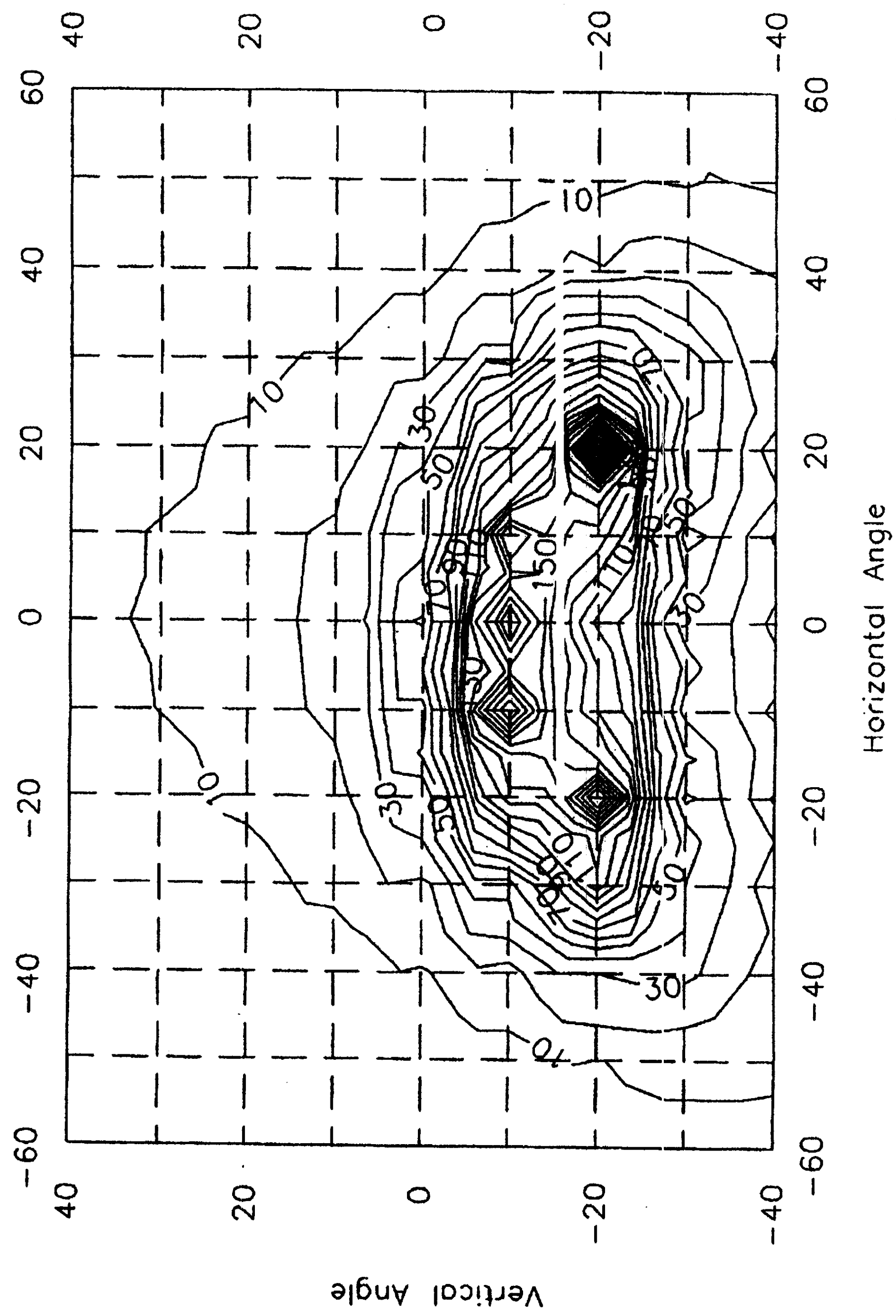


FIG. 37



Von=6.8V
R=120nm
λ=WHITE

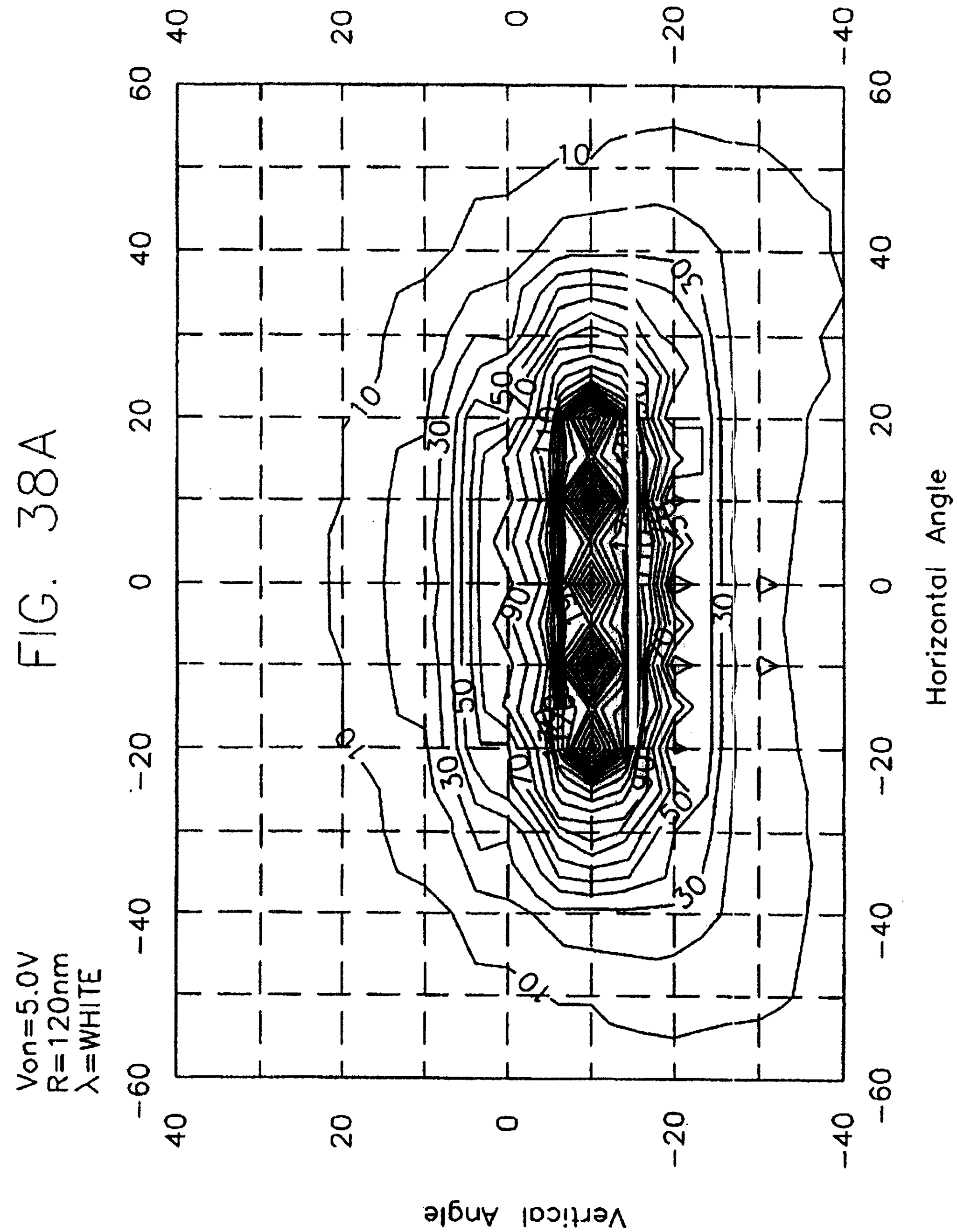

Von=5.0V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
10
30
50
70
90
110

FIG. 38A

FIG. 38B

R=120nm
λ=White

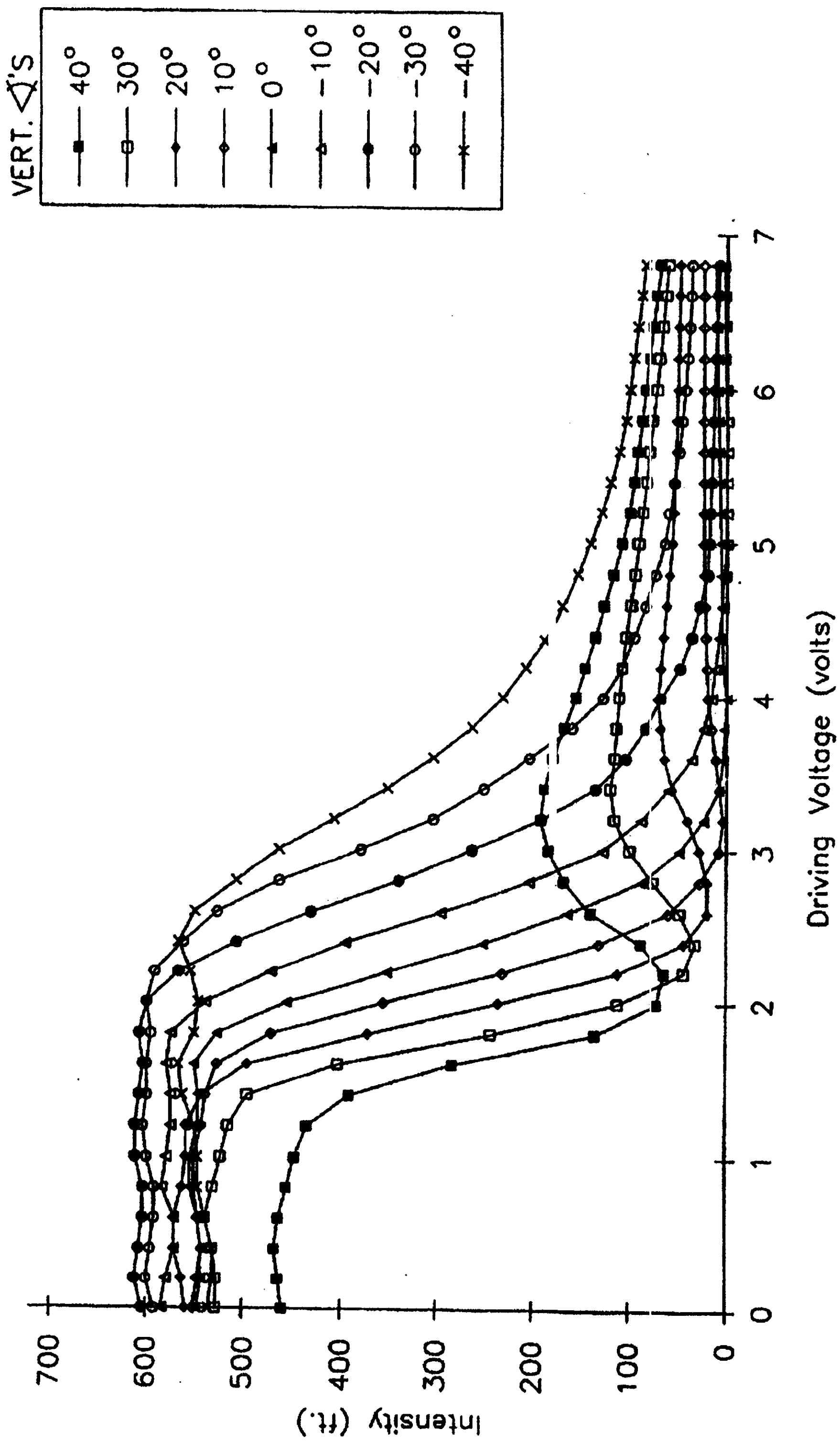


FIG. 39

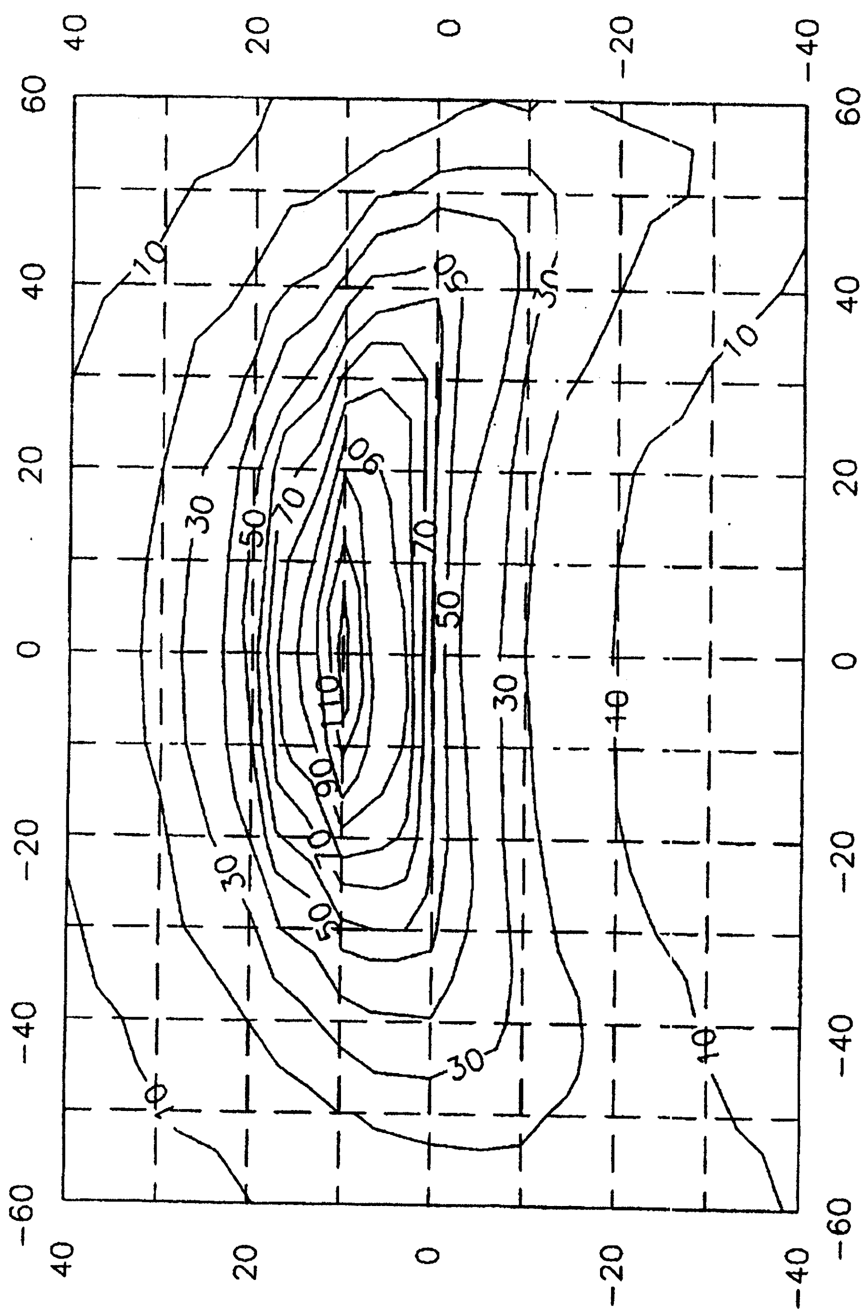


FIG. 40

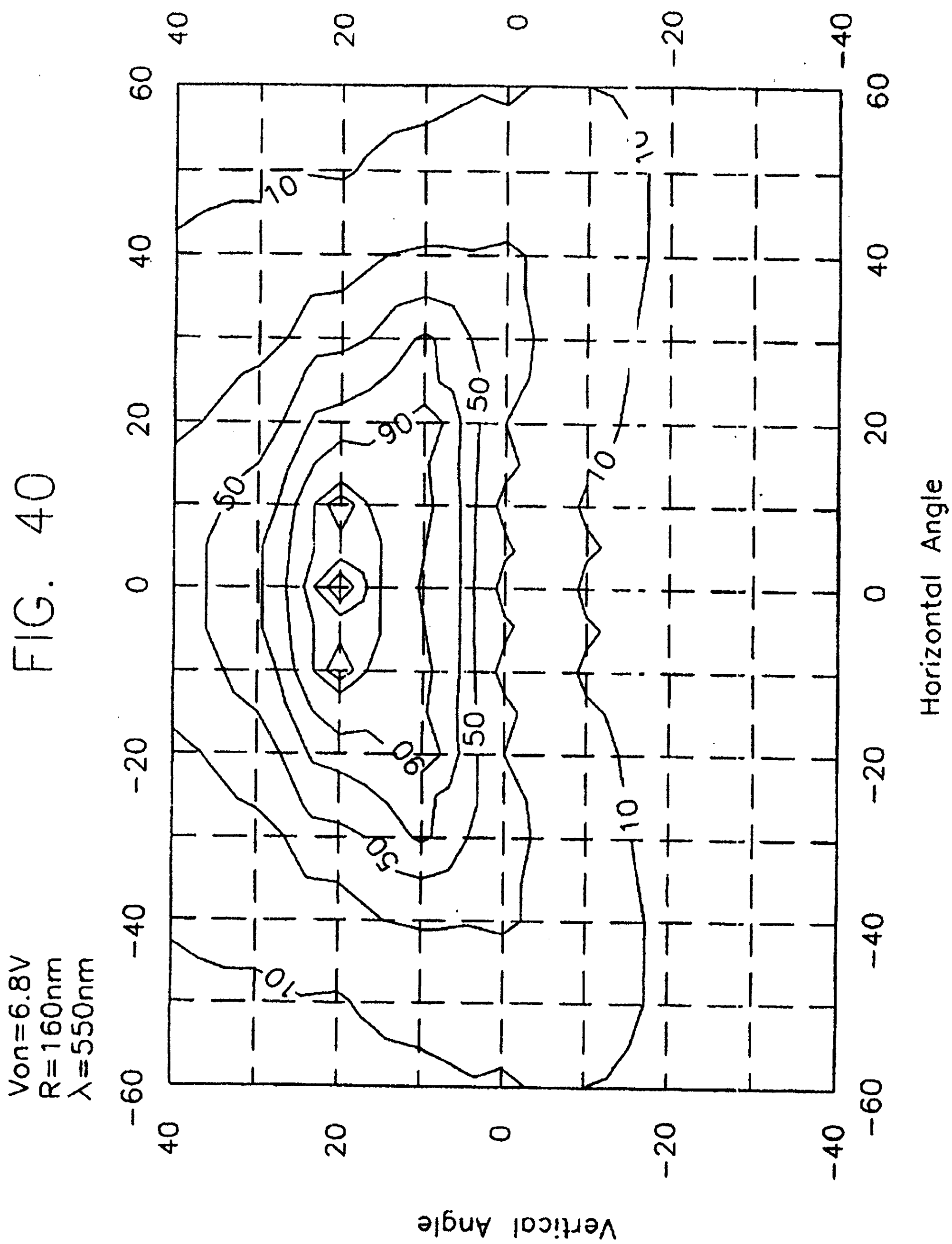

Von=6.8V
R=160nm
λ=550nm
Horizontal Angle
Vertical Angle
10
50
90

Fig. 42

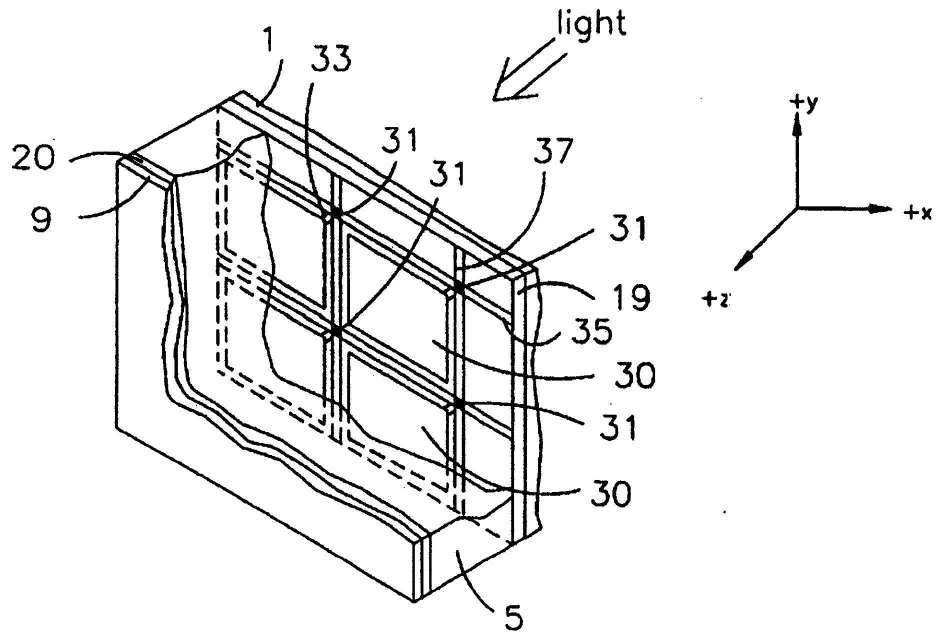

light
1
33
20
9
31
31
37
31
19
35
30
31
30
5
+y
+x
+z

Fig. 41

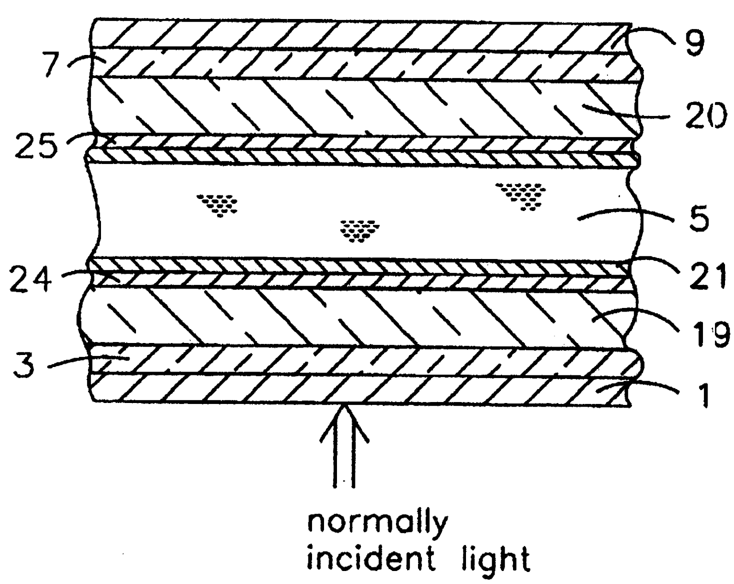
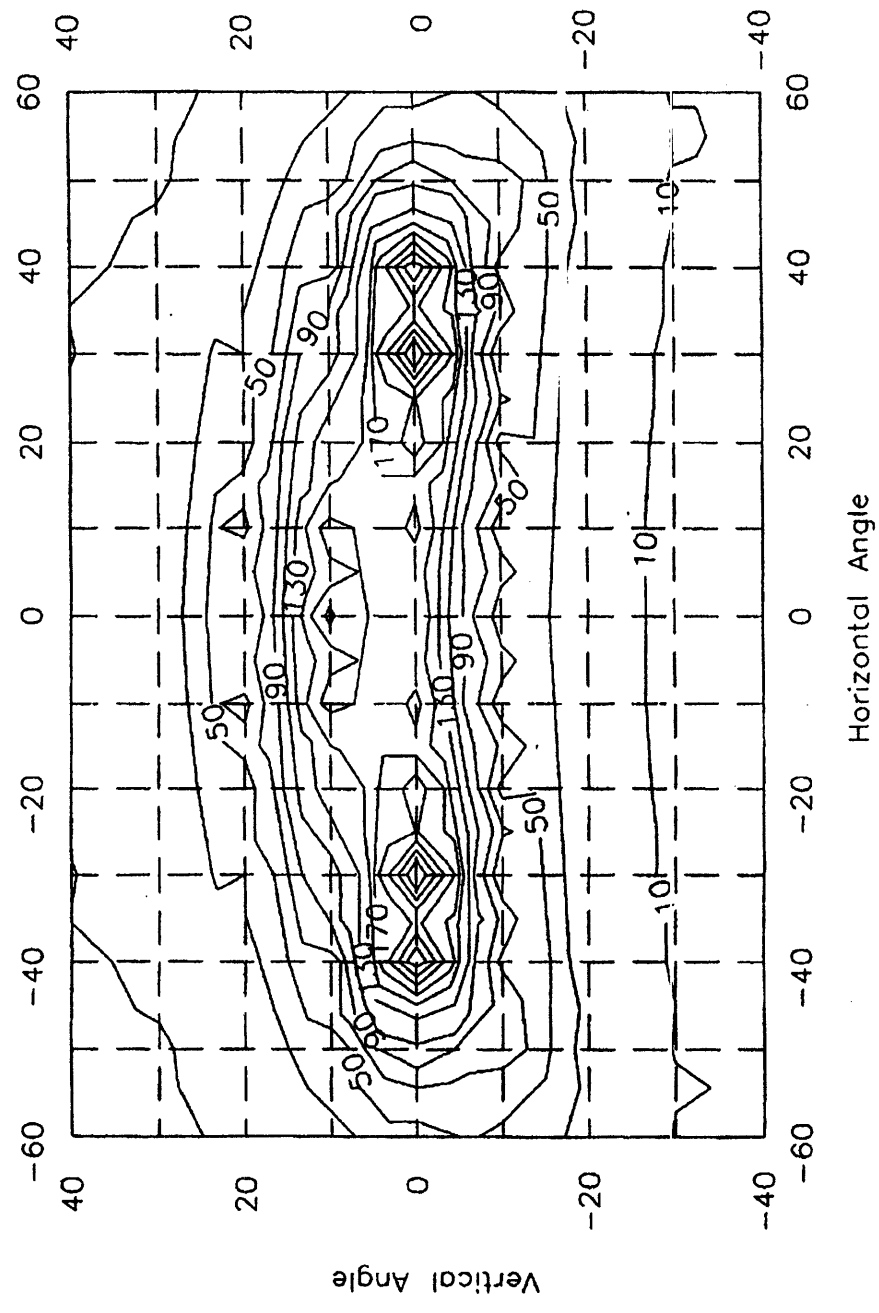

9
7
20
25
5
24
21
19
3
1
normally
incident light

FIG. 43

Von=6.0V
R=Δzx=Δzy=−160nm
λ=550nm



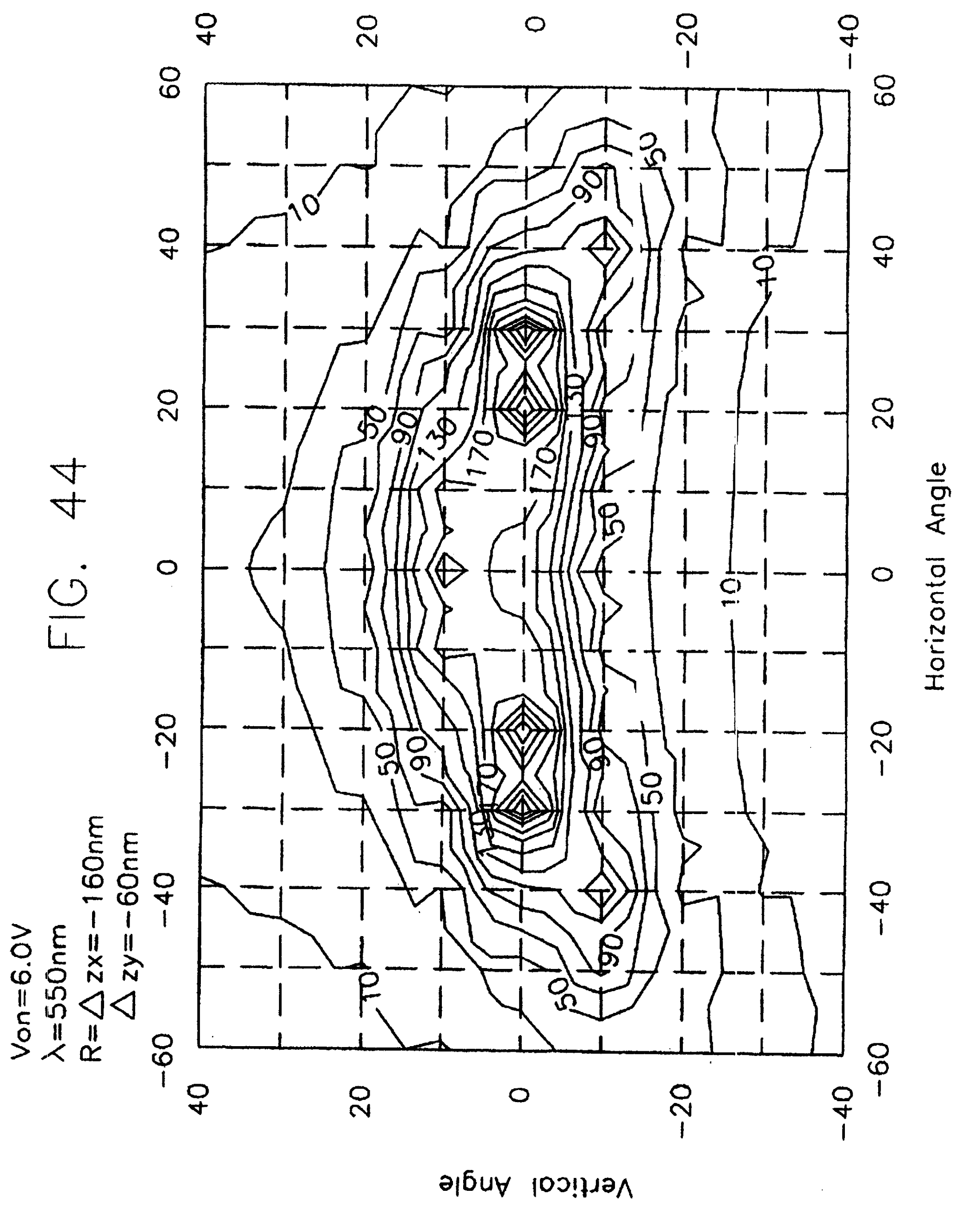
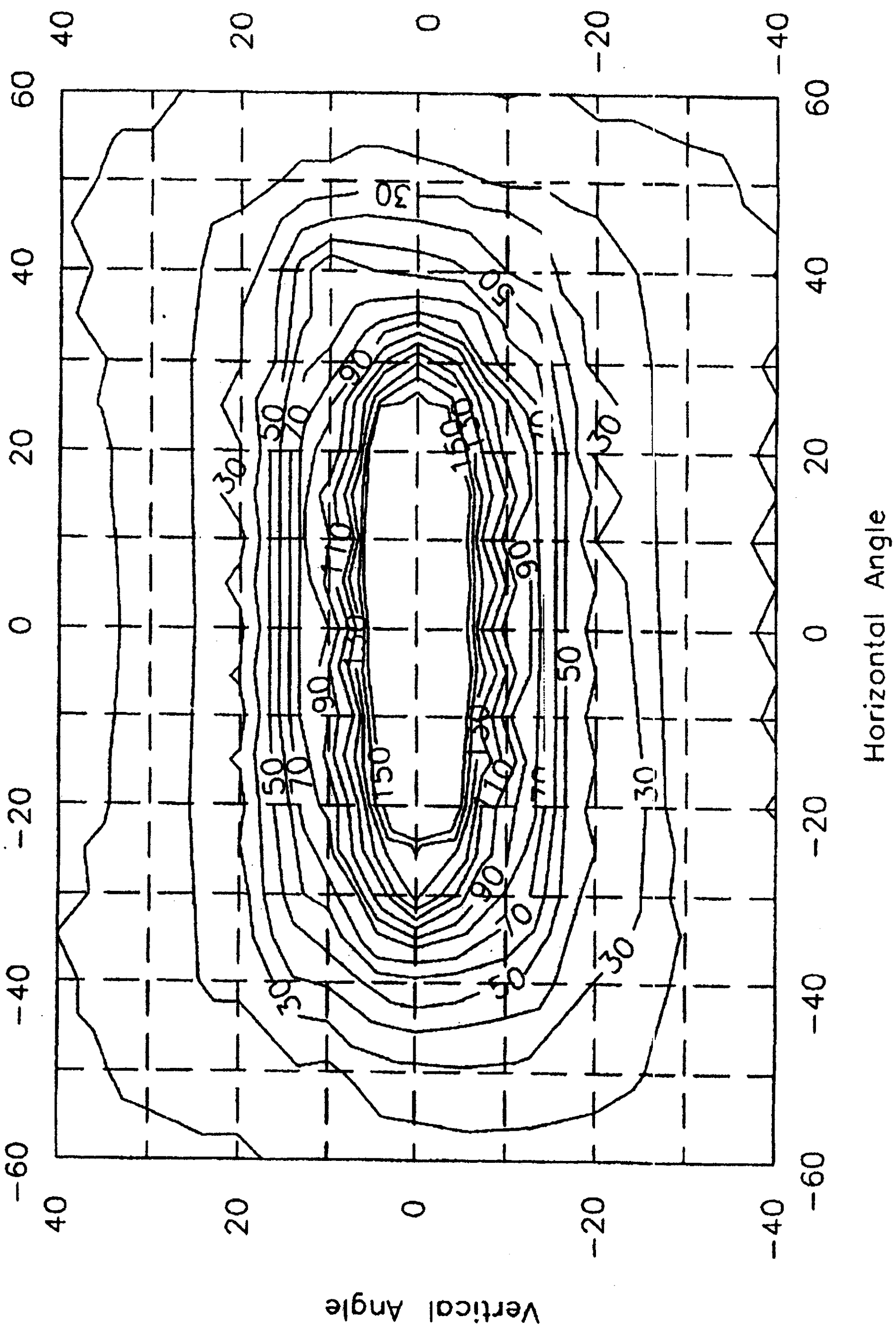

Von=6.0V
λ=550nm
R=Δzx=−160nm
Δzy=−60nm
Horizontal Angle
Vertical Angle
10
50
90
130
170

FIG. 44

FIG. 45


Von=6.0V
λ=WHITE
R=BIAXIAL
Horizontal Angle
Vertical Angle
30
50
70
90
110
130
150
-60
-40
-20
0
20
40
60

LCD INCLUDING A NEGATIVE BIAXIAL RETARDER ON EACH SIDE OF THE LIQUID CRYSTAL LAYER

This application is a continuation of Ser. No. 08/711,797, filed Sep. 10, 1996, which is a continuation of Ser. No. 08/167,652, filed Dec. 15, 1993, (now U.S. Pat. No. 5,570, 214), the disclosures of which are incorporated herein by reference.

This invention relates to a liquid crystal display having at least two retardation films, one on each side of a liquid crystal layer. More particularly, this invention relates to a normally white liquid crystal display which includes at least one retardation film having a retardation value of 80–200 nm on each side of the liquid crystal layer.

BACKGROUND OF THE INVENTION

Liquid crystal materials are useful for electronic displays because light traveling through a layer of liquid crystal (LC) material is affected by the anisotropic or birefringent value (ΔN) of the material, which in turn can be controlled by the application of a voltage across the liquid crystal material. Liquid crystal displays are desirable because the transmission or reflection of light from an external source, including ambient light and backlighting schemes, can be controlled with much less power than .was required for the illuminance materials used in other previous displays. Liquid crystal displays (LCDs) are now commonly used in such applications as digital watches, calculators, portable computers, avionic cockpit displays, and many other types of electronic devices which utilize the liquid crystal display advantages of long-life and operation with low voltage and power consumption.

The information in many liquid crystal displays is presented in the form of a matrix array of rows and columns of numerals or characters, which are generated by a number of segmented electrodes arranged in such a matrix pattern. The segments are connected by individual leads to driving electronics, which apply a voltage to the appropriate combination of segments to thereby display the desired data and information by controlling the light transmitted through the liquid crystal material. Graphic information in, for example, avionic cockpit applications or television displays may be achieved by a matrix of pixels which are connected by an X-Y sequential addressing scheme between two sets of perpendicular conductor lines (i.e. row and column lines). More advanced addressing schemes use arrays of thin film transistors, diodes, MIMS, etc. which act as switches to control the drive voltage at the individual pixels. These schemes are applied predominantly to twisted nematic liquid crystal displays, but are also finding use in high performance versions of super twisted liquid crystal displays.

Contrast is one of the most important attributes determining the quality of both normally white (NW) and normally (NB) liquid crystal displays. Contrast, or the contrast ratio, is the difference between OFF state transmission versus ON state transmission. In normally black liquid crystal displays, the primary factor limiting the contrast achievable in these LCDs is the amount of light which leaks through the display in the darkened or OFF state. In normally white (NW) LCDs, the primary factor limiting the contrast is the amount of light which leaks through the display in the darkened or ON state. These problems are compounded in a bright environment, such as sunlight, where there is a considerable amount of reflected and scattered ambient light. In color liquid crystal displays, light leakage causes severe color shifts for both saturated and gray scale colors. These limitations are particularly important for avionic applications, where the copilot's viewing of the pilot's displays is important.

In addition, the legibility of the image generated by both normally black (NB) and normally white (NW) liquid crystal display devices depends on the viewing angle, especially in the matrix address device with a large number of scanning electrodes. Absent a retardation film, the contrast ratio of a typical NB or NW liquid crystal display is usually at a maximum only within a narrow viewing (or observing) angle centered about normal incidence (0° horizontal viewing angle and 0° vertical viewing angle) and drops off as the angle of view is increased.

It would be a significant improvement in the art to provide a liquid crystal display capable of presenting a high quality, high contrast image over a wide field of view.

Normally black liquid crystal displays are quite sensitive to cell gap, or the thickness "d" of the liquid crystal material, as well as to the temperature of the liquid crystal material. Therefore, normally black liquid crystal displays must be manufactured in accordance with rather specific tolerance parameters related to the cell gap of the display making them both difficult and expensive to make. One way in which to compensate for the normally black displays high sensitivity to cell gap is to provide such a multi-colored display with a multi-gap design wherein the thickness "d" of the liquid crystal material for each colored subpixel is matched to the first transmission minimum of the color of that subpixel. See, for example, U.S. Pat. No. 4,632,514 which utilizes the multi-gap approach by varying the liquid crystal material thickness "d" for the red, green, and blue subpixels therein so as to match the thickness "d" of each subpixel to the three different transmission minimums representative of the colors red, green, and blue. This increases, of course, the difficulty and expense of manufacturing this type of LCD.

Although a normally black display is rather sensitive to temperature and cell gap "d", a significant advantage associated with this type of liquid crystal display is that it provides good contrast ratios at wide viewing angles. Thus, a viewer may satisfactorily observe the data of the display throughout a wide range of viewing angles. Contrast ratio curves of, for example, 10:1 in normally black displays often extend up to viewing angles of, for example, 0° vertical, ±60° horizontal. The fact that normally black displays have such good contrast ratios at such large horizontal viewing angles enables them to be used in commercial applications where such viewing angles are required or preferred. Furthermore, NB displays generall experience more darkened state leakage than do NW displays.

Turning now to normally White liquid crystal displays, NW displays are fairly insensitive to the temperature and cell gap "d" of liquid crystal material. This allows for the manufacturing tolerances associated with the development of normally white displays to be lessened. Hence, normally white displays are easier and cheaper to manufacture then their normally black counterparts. However, while normally white LCDs are less sensitive to temperature and cell gap than normally black LCDs, their contrast ratios at large viewing angles are generally small relative to those of normally black displays. For example, 10:1 contrast ratio curves in normally white displays often extend only up to horizontal viewing angles of about 0° vertical, ±35° horizontal. This is significantly less than the extent to which the same contrast ratio curves extend horizontally in normally black displays. Therefore, while normally white LCDs are

easier and cheaper to manufacturer than normally black liquid crystal displays, they have a smaller range of satisfactory viewing angles than do normally black displays. It would satisfy a long felt need in the art if one could provide NW display which had good contrast ratios at large viewing angles.

Several types of liquid crystal pixels or cells are in widespread use in flat panel displays. Active matrix addressing allows such displays to present a full color image with high resolution. When viewed directly at a normal or ON axis viewing angle (0° vertical, 0° horizontal viewing angle), a liquid crystal display of either the normally black or normally white type provides a generally high quality output, especially when the cell gap "d" is matched to the first transmission minimum, but the image degrades and contrast ratios decrease at increased viewing angles. This occurs because liquid crystal cells operate by virtue of the anisotropic or birefringent effect exhibited by their liquid crystal layer which includes a large number of anisotropic liquid crystal molecules. Such a material will be positively uniaxially birefringent (i.e., the extraordinary refractive index is larger than the ordinary refractive index). The phase retardation effect such a liquid crystal material has on light passing through it inherently varies or increases with the inclination angle of light, leading to lower contrast ratios and a lower quality image at larger viewing angles. By introducing an optical compensating element (or retarder) into the liquid crystal pixel or cell, however, it is possible to correct for the unwanted angular effects and thereby maintain higher contrast at both normal and larger viewing angles than otherwise possible.

The type and orientation of optical compensation or retardation required depends in part upon the type of display, normally black or normally white, which is used.

In a normally black (NB) twisted nematic display, the twisted nematic liquid crystal material is placed between polarizers whose transmission axes are parallel to one another. In the unenergized OFF state (no voltage above the threshold voltage V_{th} is applied across the liquid crystal material), normally incident light from the backlight is first polarized by the rear polarizer and in passing through the pixel or cell has its polarization direction rotated by the twist angle of the liquid crystal material dictated by the buffing zones. This effect is known as the twisting effect. The twist angle is set, for example, to be about 90° so that the light is blocked or absorbed by the front or output polarizer when the pixel is in the OFF state. When a voltage is applied via electrodes across the normally black pixel, the liquid crystal molecules are forced to more nearly align with the electric field, eliminating the twisted nematic optical effect of the LC material. In this orientation, the optical molecular axes of the liquid crystal layer molecules are perpendicular to the cell walls. The liquid crystal layer then appears isotropic to normally incident light, eliminating the twist effect such that the light polarization state is unchanged by propagation through the liquid crystal layer so that light can pass through the output polarizer. Patterns can be written in a normally black display by selectively applying a variable voltage to the portions of the display which are to appear illuminated.

Turning again to normally white (NW) LCD cells, in a normally white liquid crystal display configuration, a twisted nematic cell preferably having a twist angle of about 80°–100° (most preferably about 90°) is placed between polarizers which have substantially crossed or perpendicular transmission axes, such that the transmission axis of each polarizer is either parallel (P-buffed) or perpendicular (X-buffed) to the buffing direction or orientation of the liquid crystal molecules in the interface region of the liquid crystal material adjacent each polarizer. In other words, normally white cells can be either P-buffed where both polarizer axes are substantially parallel to their respective adjacent buffing zones, or X-buffed where both polarizer axes are substantially perpendicular to their respective adjacent buffing zones.

This NW orientation of the polarizers reverses the sense of light and dark from that of the normally black displays discussed above. The OFF or unenergized (no applied voltage above V_{th} across the liquid crystal material) areas appear light in a normally white display, while those which are energized appear dark.

The problem of ostensibly dark areas appearing light or colored when viewed at large angles still occurs, however, thereby creating the aforesaid lowered contrast ratios at reasonably large viewing angles. The reason for the reduced contrast ratios at large viewing angles in normally white displays is different than the reason for the problem in normally black displays. In the normally white energized darkened areas, the liquid crystal molecules tend to align with the applied electric field. If this alignment were perfect, all of the liquid crystal molecules in the cell would have their long axes normal to the glass substrate or cell wall. In the energized state, the normal white display appears isotropic to normally incident light, which is blocked by the crossed polarizers, thus, resulting in a darkened pixel or subpixel.

The loss of contrast with increased viewing angles in normally white pixels or displays occurs primarily because the homeotropic livid crystal layer does not appear isotropic to OFF axis or OFF normal light. Light directed at OFF normal angles through the liquid crystal material propagates in two modes due to the anisotropy or birefringence (ΔN) of the liquid crystal layer, with a phase delay between these modes which increases with the incident angle of light. This phase dependence on the incident angle introduces an ellipticity to the polarization state which is then incompletely extinguished by the front or exit polarizer in the normally white cell, giving rise to light leakage. Because of the normally white symmetry the birefringence has no azimuthal dependence.

Accordingly, what is needed in normally white displays is an optical compensating or retarding element which introduces a phase delay that restores the original polarization state of the light, allowing the light to be blocked by the output polarizer in the ON state. Optical compensating elements or retarders for normally white displays are known in the art and are disclosed, for example, in U.S. Pat. Nos. 5,184,236; 5,196,953; 5,138,474; and 5,071,997, the disclosures of which are hereby incorporated herein by reference. It is known that the polyimides and copolyimides disclosed by aforesaid U.S. Pat. No. 5,071,997 can be used as negative birefringent retarding elements in normally white liquid crystal displays and are said to be custom tailorable to the desired negative birefringent values without the use of stretching. The polyimide retardation films of No. 5,071,997 are uniaxial but with an optical axis oriented in the Z direction which is perpendicular to the plane defined by the film.

Quite often, the retardation films or plates used in conjunction with normally white displays have a negative birefringent value. However, in certain cases, retardation films, having a positive birefringent value are used in combination with such normally white cells. An example of this is U.S. Pat. No. 5,184,236 which will be discussed more fully below.

FIG. 1 is a contrast ratio curve graph for a prior art normally white light valve pixel. The light valve for which the contrast ratio curves are illustrated in FIG. 1 includes a rear polarizer having a transmission axis defining a first direction, a front or exit polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another, a liquid crystal material having a cell gap "d" of 5.86 μm, a rear buffing zone oriented in the second direction, and a front buffing zone orientated in the first direction. The temperature was 34.4° C. when the graph illustrated by FIG. 1 was plotted. This light valve pixel did not include a retarder. The above-listed parameters with respect to FIG. 1 are also applicable to FIGS. 2 and 3.

The contrast ratio graph of FIG. 1 was plotted utilizing a 6.8 V driving voltage V_{ON}, and a 0.2 volt V_{OFF}. As can be seen in FIG. 1, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis only to angles of about −40° horizontal and +38° horizontal. Likewise, the 30:1 contrast ratio curve extends along the 0° vertical viewing axis only to horizontal angles of about ±30°. This graph is illustrative of the problems associated with normally white liquid crystal displays in that their contrast ratios at large horizontal and vertical viewing angles are fairly low.

FIG. 2 is a contrast ratio curve graph for the normally white light valve described above with respect to FIG. 1. However, the FIG. 2 graph was plotted utilizing a V_{ON} of 5.0 volts and a V_{OFF} of 0.2 volts. Again, the temperature was 34.4° C. As can be seen by comparing the graphs of FIG. 1 and FIG. 2, as the voltage applied to the liquid crystal material decreases, as in FIG. 2, the contrast ratio curves expand horizontally and contract vertically. The 10:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends a total of about 85° as opposed to only 78° in FIG. 1. Also, the 30:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends horizontally about 67° as opposed to only about 58° in FIG. 1. With respect to vertical viewing angles, the contrast ratio curves of 10:1 and 30:1 in FIG. 2 do not extend along the 0° horizontal viewing axis to the negative vertical extent that they did in FIG. 1. Accordingly, while the normally white light valve of FIGS. 1–3 has less than desirable contrast ratios at large viewing angles, the contrast ratios expand horizontally and contract vertically as the voltage across the liquid crystal material decreases.

FIG. 3 is a driving voltage versus intensity plot for the light valve pixel described above with respect to FIGS. 1–2 illustrating the gray level characteristics of the pixel. The various curves represent horizontal viewing angles from −60° to +60° along the 0° vertical viewing axis.

Gray level performance of a liquid crystal display is very important. Conventional liquid crystal displays utilize anywhere from about eight to sixty-four different driving voltages. The different driving voltages are referred to as "gray level" voltages. The intensity of the light transmitted through the pixel or display depends upon the driving voltage. Accordingly, gray level voltages are used to generate different shades of different colors and to create different colors when these shades are mixed with one another. Preferably, the higher the driving voltage in a NW display, the lower the intensity of light transmitted therethrough. Likewise then, the lower the driving voltage, the higher the intensity of light emitted from the preferred forms of a normally white display. The opposite is true in a normally black display. Thus, by utilizing multiple gray level driving voltages, one can manipulate either an NW or NB liquid crystal display pixel to emit a desired intensity of light. A gray level V_{ON} is any voltage greater than V_{th} up to about 5.0–6.5 V.

Gray level intensity performance for LCDs is dependent upon the displays' driving voltage. It is desirable in gray level performance of NW displays to have an intensity versus driving voltage curve wherein the intensity of the light emitted from the pixel continually and monotonically decreases as the driving voltage increases. In other words, it is desirable to have gray level performance in a pixel such that the intensity at 6.0 volts is less than that at 5.0 volts, which is in turn less than that at 4.0 volts, which is less than that at 3.0 volts, which is in turn less than that at 2.0 volts, etc. Such good gray level curves across wide ranges of viewing angles allow the intensity of radiation emitted from the pixel to be easily controlled.

Turning again now to FIG. 3, the intensity versus driving voltage curves illustrated therein with respect to the prior art light valve pixel of FIGS. 1–2 having no retardation film are undesirable because of the inversion hump present in the area of the curves having voltages greater than about 3.2 volts. The term "inversion hump" means that the intensity aspect of the curve monotonically decreases as the driving voltage increases in the range of about 1.6–3.0 volts, but at a driving voltage of about 3.2 volts, the intensities at a plurality of viewing angles begin to rise as the voltage increases from about 3.2 volts to 6.8 volts. This rise in intensity as the voltage increases is known as an "inversion hump." The inversion hump of FIG. 3 includes only a rise portion. However, such inversion humps often include both a rise and fall portion. The presence of this inversion hump with respect to a plurality of horizontal viewing angles as shown in FIG. 3 means that as gray level voltages between, for example, 1.6 and 3.0 volts increase, the intensity of radiation emitted from the pixel decreases accordingly. However, as gray level voltages above 3.0 volts increase from 3.2 volts all the way up to 6.8 volts, the intensity of radiation emitted from the pixel increases. This is undesirable. A perfect driving voltage versus intensity curve would have a decreased intensity for each increase in gray level driving voltage. In contrast to this, the inversion hump represents an increase in intensity of radiation emitted from the light valve pixel for each increase in gray level driving voltage above about 3.2 volts for certain viewing angles. Accordingly, it would satisfy a long felt need in the art if a liquid crystal display and pixels therein could be provided with no or little inversion. In other words, the smaller the rise in intensity for an increase in driving voltage at all gray levels, the better.

FIG. 4 is a schematic illustration showing an optical arrangement of a normally white liquid crystal display device disclosed in U.S. Pat. No. 5,184,236. As illustrated, the LCD includes a rear polarizer 111, a rear retardation plate or film 113, a liquid crystal cell 119 including a liquid crystal material sandwiched between a rear orientation or buffing zone oriented in direction A_0 and a front orientation or buffing zone oriented in direction A_1, a front retardation film 114, and finally a front polarizer 112.

The rear polarizer 111 is provided at the light incident side of the liquid crystal layer 119, a front or exit polarizer 112 is provided at the light exit side of the liquid crystal layer 119, a rear retardation film 113 is provided between the liquid crystal layer and the polarizer 111, and a front retardation film 114 is provided between the liquid crystal layer and the front polarizer 112. This prior art NW display is "P-buffed" because the rear polarizer transmission axis P_1 is parallel to the rear orientation direction A_0, and the front polarizer transmission axis P_2 is parallel to the front orientation direction A_1.

The product of parameters "ΔN·d" of the liquid crystal layer 119 is set in the range of 450–550 nm. The liquid crystal material of U.S. Pat. No. 5,184,236 is left handed as defined in the art. The aligning direction of the rear orientation film on the light incident side of the liquid crystal layer 109 is a rubbing direction A_0 inclined at approximately 45° with respect to the side of the liquid crystal cell. The aligning direction of the orientation or buffing film on the front side of the liquid crystal layer is oriented in direction A_1 which is rotated about 90° in a counterclockwise direction from the orientation direction A_0 of the orientation film on the rear side of the liquid crystal material. Therefore, the liquid crystal layer 119 sandwiched between the opposing orientation films is twisted substantially 90°. The pretilting angle of the liquid crystal molecules is approximately 1°.

The rear linear polarizer 111 has a transmission axis P_1 which is parallel to the orientation direction A_0, while the front polarizer 112 has a transmission axis direction P_2 which is parallel to the front orientation direction A_1. The transmission axes of the front and rear polarizers 112 and 111 are perpendicular to one another thereby defining a normally white liquid crystal display. The rear retardation plate or film 113 is so arranged that its optical axis R_1 is either parallel to or crosses at 90° to the rear rubbing direction A_0. The front retardation film 114 is so arranged that its optical axis R_2 is either parallel to or crosses at 90° to the rubbing direction A_1. These retardation films 113 and 114 are formed to have equal retardation values (d·ΔN) where "d" is the thickness of the retardation film and "ΔN" is the anisotropic or birefringent value of the retardation film. The retardation values of the retardation films 113 and 114 are set in the range of 300–400 nm. The front and rear retardation films are formed of the same material such as, for example, a polycarbonate or polyvinyl alcohol, and the outer surfaces thereof are preferably covered with a protective film made of triacetyl cellulose or the like.

The orientation or buffing directions of prior art FIG. 4 are "six o'clock buffed." The term "six o'clock buffed" means that the rear and front orientation directions A_0 and A_1 are oriented in directions so as to provide a viewing zone having an extended region in the six o'clock area of the graphs shown in FIGS. 5A–5D. In other words, because the orientation direction A_0 goes from the upper left to the lower right as shown in FIG. 4, and orientation direction A_1 goes from lower left to upper right, the resulting viewing zone has better contrast as shown in FIGS. 5A–5D in the negative vertical region below the 0° vertical viewing axis. This is what is meant by the phrase "six o'clock buffed."

Alternatively, if the orientation direction A_0 went from the lower right to the upper left, and the orientation direction A_1 was directed from the upper right to the lower left, then the display of FIG. 4 would have been "twelve o'clock buffed" and would have provided a viewing zone having better contrast ratios in the positive vertical viewing angles instead of the negative vertical viewing angles. The six o'clock buffed LCDs of FIGS. 4 and 5A–5D illustrate viewing zones with better contrast ratios in the negative vertical area below the 0° vertical viewing axis as opposed to the positive vertical viewing area above the 0° vertical viewing axis.

In the prior art liquid crystal display of FIG. 4, the contrast ratios are measured in FIGS. 5A–5D for the four possible cases of retardation film orientation, when the value of d·ΔN of a liquid crystal layer 119 is set to 510 nm and the retardation value of both retardation films 113 and 114 is set to 350 nm (the value measured by the light having a wavelength of 589 nm). The four cases are as follows.

FIG. 5A shows contrast ratio curves for the case where the optical axes of the rear and front retardation films 113 and

114 are disposed together in parallel to the rear rubbing direction A_0. The solid or outer contrast ratio curve in FIGS. 5A–5D represents a contrast ratio of 10:1. The inner or equally broken contrast curve in FIGS. 5A–5D represents a contrast ratio of 100:1. The intermediate contrast ratio curve in FIGS. 5A–5D represents a contrast ratio of 50:1. Furthermore, in the graphs of FIGS. 5A–5D, each circle represents a 10° shift in viewing angle. In other words, the center of the graph represents a 0° vertical and 0° horizontal viewing angle, the first circle represents 10°, the second circle 20°, etc. As can be seen in FIG. 5A, the 10:1 contrast ratio curve extends horizontally along the vertical 0° viewing axis to about −37° and +40°, and extends upwardly along the 0° horizontal viewing axis to about 15° vertical.

FIG. 5B shows contrast ratio curves for the case where the optical axis R_1 of the rear retardation film 113 is disposed in parallel to the orientation direction A_0, and the optical axis R_2 of the front retardation film 114 is disposed perpendicular to the rubbing direction A_0. The direction R_1 is parallel to the rear polarizer axis P_1, and R_2 is parallel to the front polarizer axis P_2. As can be seen in FIG. 5B, the 10:1 contrast ratio curve extends along the 0° horizontal viewing axis only to about 15° vertical. Also, the 50:1 contrast ratio curve extends along the 0° horizontal viewing axis only about 5° vertical.

FIG. 5C shows contrast ratio curves for the case where the optical axes of the rear and front retardation films 113 and 114 are arranged in parallel with one another and cross at 90° to the rear buffing direction A_0. In FIG. 5C, the 10:1 contrast ratio curve extends upward along the 0° horizontal viewing axis only to about 15° vertical. Also, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis a total of about 75°–80°.

FIG. 5D shows contrast ratio curves for the case where the optical axis R_1 of the rear retardation film 113 is arranged to cross at 90° to the rubbing direction A_0, and the optical axis R_2 of the front retardation film 114 is arranged in parallel to rear orientation direction A_0. In FIG. 5D, the 10:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis a total of about 60°–65°. Also, the 10:1 contrast ratio curve in FIG. 5D extends upward along the 0° horizontal viewing axis only to about +15° vertical.

It was known prior to our invention to rotate retardation films to adjust the viewing zones of LCDs. For example, U.S. Pat. No. 5,184,236 teaches rotating the optical axes of retardation films ±15° or less when two such films are disposed on a single side of the liquid crystal material. The axes of the retardation films are rotated either in the clockwise or counterclockwise direction for the purpose of adjusting the viewing zone. However, when the retardation films of this patent are rotated, the symmetry of the viewing zone is substantially distorted thereby creating viewing zones which are not substantially symmetrical about the 0° horizontal viewing axis. Furthermore, this patent does not teach rotating one or both optical axes of rear and front retardation films ±15° or less for the purpose of adjusting the location of the display's viewing zone when the display includes rear and front retardation films with a liquid crystal layer therebetween.

FIG. 6 illustrates the angular relationships between the horizontal and vertical viewing axes and angles described herein relative to a liquid crystal display and conventional LCD angles ϕ and θ. The +X, +Y, and +Z axes shown in FIG. 6 are also defined in other figures herein. Furthermore, the "horizontal viewing angles" (or X_{ANG}) and "vertical viewing angles" (or Y_{ANG}) illustrated and described herein may be

transformed to conventional LCD angles ϕ and θ by the following equations:

$$\mathrm{TAN}(X_{ANG})=\mathrm{COS}(\phi)\cdot\mathrm{TAN}(\theta)$$

$$\mathrm{SIN}(Y_{ANG})=\mathrm{SIN}(\theta)\cdot\mathrm{SIN}(\phi)$$

or

$$\mathrm{COS}(\theta)=\mathrm{COS}(Y_{ANG})\cdot\mathrm{COS}(X_{ANG})$$

$$\mathrm{TAN}(\phi)=\mathrm{TAN}(Y_{ANG})\div\mathrm{SIN}(X_{ANG})$$

FIGS. 7–10 are computer simulation contrast ratio curve graphs of a normally white liquid crystal display having a cell gap "d" of 5.70 μm. The display includes a rear polarizer having a transmission axes defining a first direction, a rear retardation film having an optical axis parallel to the first direction, a rear buffing zone oriented perpendicular to the first direction, a front buffing zone parallel to the first direction, a front retardation film having an optical axis perpendicular to the first direction, and a front or exit polarizer having a transmission axis perpendicular to the first direction. The retardation films are of the positively birefringent uniaxial type. This LCD of FIGS. 7–10 is not prior art to this invention but is included in this section for the purpose of later comparison with certain embodiments of this invention.

FIG. 7 is a computer simulation contrast ratio graph of the aforesaid normally white liquid crystal display wherein the wavelength of light utilized was red at 630 nm, V_{ON} was 6.8 volts, and V_{OFF} was 0.9 volts. The retardation value of both the front and rear retardation films of the display simulated in FIGS. 7–10 was 320 nm. As can be seen in FIG. 7, the 10:1 contrast ratio curve extends along the 0° vertical viewing angle from horizontal angles of about −40° to +40° thereby defining along the 0° vertical viewing axis a 10:1 total viewing zone of about 80°.

FIG. 8 is a computer simulation graph of the aforesaid display also simulated by FIG. 7. The difference between the graph of FIG. 8 and the graph of FIG. 7 is that a 5.0 V_{ON} was used as a parameter in FIG. 8. As can be seen, a reduction in V_{ON} results in a shifting upward of the viewing zone to a position centered substantially above the 0° vertical viewing axis. Also, a reduction in V_{ON} results in a vertical shrinking of the viewing zone.

FIG. 9 is a computer simulation graph illustrating the contrast ratios of the aforesaid display wherein the retardation value of the front and rear retardation films is 320 nm, and the parameter V_{ON} is 6.8 volts. The difference between the graph of FIG. 7 and the graph of FIG. 9 is that a green wavelength of 550 nm was used in FIG. 9. The reason for the higher contrast for the green wavelength as opposed to the red wavelength of FIG. 7 is that the cell gap of 5.70 μm is more nearly matched to the first transmission minimum for the green wavelength than that of the red wavelength. Accordingly, the green wavelength experiences higher contrast ratios in the center of its viewing zone. Again, the 10:1 contrast ratio curve in FIG. 9 extends horizontally along the 0° vertical viewing axis a total of about 75°.

FIG. 10 is a computer simulation graph of the aforesaid display wherein a blue wavelength of 480 nm was used. As in the graphs of FIGS. 7–9, the retardation value for the rear and front retardation films or plates was 320 nm. The 10:1 blue contrast ratio curve shown in FIG. 10 extends horizontally along the 0° vertical viewing axis a total of about 75°. The blue contrast ratio viewing zone is shifted slightly upward from that shown in FIG. 7 with respect to the red wavelength.

As can be seen from the contrast ratio curves of FIGS. 1, 2, and 7–10, it would be highly desirable if one could provide a normally white liquid crystal display with a viewing zone including contrast ratio curves which extended to large horizontal and vertical viewing angles.

U.S. Pat. No. 4,984,874 discloses a liquid crystal display device having front and rear retardation films having retardation values of about 300 nm. A liquid crystal layer including front and rear buffing zones is sandwiched between the retardation films. The rear retardation film functions so as to convert linearly polarized light into elliptically polarized light while the front retardation film converts elliptically polarized light exiting the liquid crystal material into linear polarized light before it reaches the front or exit polarizer. The twist angle of the liquid crystal material of U.S. Pat. No. 4,984,874 is about 180°–270°.

U.S. Pat. No. 5,107,356 discloses a normally black liquid crystal display including first and second polarizers having parallel transmission axes. A liquid crystal material of this patent is sandwiched between front and rear retardation films.

While it is known to dispose rear and front 300–600 nm retardation films or plates on opposite sides of a liquid crystal layer of a P-buffed display, the prior art does not disclose providing a normally white X-buffed liquid crystal display or pixel with rear and front retardation films having 80–200 nm retardation values in order to achieve a high contrast ratio over a predetermined range of viewing angles. The prior art also does not disclose symmetrically rotating the optical axes of such rear and front retardation films so as to shift the centered position of the display's viewing zone to a point below the 0° vertical viewing axis, and thus, away from inversion areas present above the 0° vertical viewing axis.

The terms "clockwise" and "counterclockwise" as used herein mean as viewed from the viewer's or observer's side of the liquid crystal display or pixel.

The term "rear" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones, retardation films, and orientation films means that the described element is on the incident light side of the liquid crystal material, or in other words, on the side of the liquid crystal material opposite the viewer.

Each of the displays and light valves described herein is/was "X-buffed" unless otherwise shown or described.

The term "front" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones, retardation films, and orientation films means that the described element is located on the viewer side of the liquid crystal material.

The LCDs and light valves of FIGS. 1–3 and 7–45 herein include left handed liquid crystal material with a birefringence (ΔN) of 0.084 at room temperature.

The term "retardation value" as used herein means "d·ΔN" of the retardation film or plate, wherein "d" is the film thickness and "ΔN" is the film birefringence (either positive or negative).

The term "interior" when used herein to describe a surface or side of an element, means the side or surface closest to the liquid crystal material.

The term "light valve" as used herein means a liquid crystal display pixel including a rear polarizer, a rear retardation film (unless otherwise specified), a rear transparent substrate, a rear continuous electrode, a rear orientation film, a LC layer, a front orientation film, a front continuous pixel electrode, a front substrate, a front retardation film (unless otherwise specified), and a front polarizer in that order,

without the presence of color filters and driving active matrix circuitry such as TFTs.

The term "contrast ratio" as used herein means the transmission of light through the display or pixel in the OFF or white state versus the amount of transmission through the display or pixel in the ON or darkened state.

It is apparent from the above that there exists a need in the art for a normally white liquid crystal display wherein the viewing zone of the display includes high contrast ratios at extended or large vertical and horizontal viewing angles. There also exists a need in the art to center the viewing zone of a NW LCD at a position distant from inversion areas present at or above the 0° vertical viewing axis.

SUMMARY OF THE INVENTION

Generally speaking this invention fulfills the above-described needs in the art by providing a liquid crystal display comprising:

a plurality of pixels, each of these pixels being comprised of a pair of driving electrodes and a twisted nematic liquid crystal material located therebetween, the liquid crystal material being of a thickness "d" and having an anisotropy ΔN such that the product of $d \cdot \Delta N$ is about 400–550 nm and wherein the liquid crystal material is capable of twisting at least one normally incident visible wavelength of light passing therethrough in an amount of about 80°–100°;

a rear, light-entrance polarizer having a transmission axis oriented in a first direction;

a front, light-exit polarizer having a transmission axis oriented in a second direction with respect to the first direction thereby to define a normally white display;

a rear retardation film disposed between the rear polarizer and the twisted nematic liquid crystal material;

a front retardation film disposed between the front polarizer and the liquid crystal material; and

wherein the transmission axes of the polarizers and optical axes of the retardation films are so arranged each with respect to the others so as to achieve a white light contrast ratio of at least about 10:1 over a horizontal angular span of at least about 100° and over a vertical angular span of greater than about 55°.

In the preferred forms of this invention contrast ratios of at least about 10:1 over a horizontal angular span of at least about 120° and over a vertical angular span greater than about 60° are achieved; particlarly when about 6.0 volts is applied to the display.

In still further preferred forms of this invention the above-described 10:1 contrast ratios are achieved while at the same time 30:1 contrast ratios of at least about 80° over the horizontal angular span and about 30° over the vertical angular span are also achieved. In a particularly preferred form of this invention, furthermore, not only are the above-described ratios achieved but a contrast ratio of about 50:1 is also achieved over a horizontal angular span of about 85° and over a vertical angular span of about 30°. In such embodiments, furthermore, it is preferred to design the display so that the product of

$$\frac{d \cdot \Delta N}{\lambda}$$

is approximately matched to the first minimum of a single, pre-selected color whose wavelength is λ. Such a color is usually red, green, or blue, but may be any other color desired.

In addition, this invention further fulfills the above-described needs in the art by providing a normally white liquid crystal display including a plurality of pixels comprising: a twisted nematic liquid crystal layer which twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough; a first retardation film on a first side of said liquid crystal layer; a second retardation film on a second side of said liquid crystal layer whereby said liquid crystal is disposed between said first and second retardation films; and wherein said first and second retardation films each are uniaxial and have positive or negative retardation values of from about 80–200 nm, and wherein the optical axes of the retardation films are so arranged each with respect to the other so as to achieve a high contrast ratio over a predetermined range of viewing angles.

In certain preferred embodiments of this invention, the first and second retardation films each have an optical axis, and wherein the optical axis of the first retardation film defines a first direction and the optical axis of the second retardation film defines a second direction, and wherein the first and second directions are different by about 75°–100°.

In certain other preferred embodiments of this invention the display further includes a first polarizer substantially adjacent the first retardation film and a second polarizer substantially adjacent the second retardation film, whereby the first and second retardation films are disposed between the first and second polarizers.

In certain further preferred embodiments of this invention the display when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 20:1 at viewing angles of about 0° vertical, ±45° horizontal.

In still further preferred embodiments of this invention the display when about 6.0 volts is applied thereto has a white light contrast ratio of at least about 20:1 at viewing angles of about −20° vertical, ±40° horizontal.

This invention further fulfills the above-described needs in the art by providing a pixel for a liquid crystal display comprising: a rear, light-entrance polarizer having a transmission axis oriented in a first direction; a front, light-exit polarizer having a transmission axis oriented in a second direction with respect to the first direction thereby to define a normally white pixel; a rear uniaxial retardation film disposed between the rear polarizer and a twisted nematic liquid crystal material, wherein the liquid crystal material twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough; a front uniaxial retardation film disposed between the front polarizer and the liquid crystal material; and wherein the front and rear retardation films have positive birefringent values and both have retardation values of from about 80–200 nm, and wherein the transmission axes of said polarizers and optical axes of said retardation films are so arranged each with respect to the others so as to achieve a high contrast ratio over a predetermined range of viewing angles.

In still other preferred embodiments of this invention the pixel has a white light contrast ratio when about 6.0 volts is applied to the pixel of at least about 30:1 at viewing angles of about (i) 0° vertical, −40° horizontal; (ii) 0° vertical, 30° horizontal; (iii) 25° vertical, 0° horizontal; and (iv) −5° vertical, ±25° horizontal.

In certain further preferred embodiments of this invention a pixel has a white light contrast ratio when about 6.0 volts is applied to the pixel of at least about 10:1 at viewing angles of about (i) 0° vertical, ±60° horizontal; (ii) 30° vertical, 0° horizontal; and (iii) −15° vertical, ±30° horizontal.

In certain further preferred embodiments of this invention an angle of from about 80°–100° is defined between the optical axes of the rear and front retardation films. In still

further preferred embodiments of this invention an angle of from about 85°–90° is defined between the optical axes of the rear and front retardation films.

This invention further fulfills the above-described needs in the art by providing a liquid crystal display having a viewing zone centered substantially below the 0° vertical viewing axis, comprising: a first polarizer having a transmission axis defining a first direction; a second polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another thereby defining a normally white display; a first retardation film having an optical axis and a positive or negative retardation value of from about 80–250 nm; a second retardation film having an optical axis, a twisted nematic liquid crystal layer disposed between the first and second retardation films wherein the liquid crystal layer twists at least one normally incident visible wavelength of light about 80°–100° as it passes therethrough; wherein the optical axes of the first and second retardation films define an angle δ therebetween of from about 70°–89° thereby creating a display having its highest contrast viewing zone centered substantially below the 0° vertical viewing axis and remote from inversion areas present above said 0° vertical viewing axis when a voltage of from about 5.0–7.0 volts is applied to the liquid crystal layer.

In certain further preferred embodiments of this invention the angle δ between the optical axes of the rear and front retardation films is from about 75°–87° thereby positioning and centering the high contrast viewing zone so as to avoid an inversion area of viewing angles located above the 0° vertical axis viewing angle and wherein said retardation films are positively birefringent.

In still further preferred embodiments of this invention the optical axis of the first retardation film and the transmission axis of the first polarizer define an angle θ1 between the rear retardation film optical axis and the rear polarizer transmission axis of from about 1.5°–7.5° therebetween.

In still further preferred embodiments of this invention the optical axis of the second retardation film and the transmission axis of the second polarizer define an angle θ2 between the front retardation film optical axis and the front polarizer transmission axis of from about 1.5°–7.5° therebetween.

In other preferred embodiments of this invention the angles θ1 and θ2 are substantially equal thereby creating a high contrast viewing zone which is substantially symmetrical about the 0° horizontal viewing axis.

This invention further fulfills the above-described needs in the arts by providing a method of shifting the highest contrast viewing zone of a liquid crystal display to a centered position away from an inversion area, comprising the steps of: a) providing the livid crystal display with a first polarizer having a transmission axis defining a first direction; b) providing the display with a second polarizer having a transmission axis defining a second direction; c) positioning the first and second polarizers on opposite sides of a twisted nematic liquid crystal layer which twists at least one wavelength of normally incident visible light about 80°–100° when it passes therethrough; d) positioning first and second positively birefringent uniaxial retardation films with substantially equal retardation values on opposite sides of the liquid crystal layer wherein the first retardation film is substantially adjacent the first polarizer, and the second retardation film is substantially adjacent the second polarizer; e) orienting an optical axis of the first retardation film relative to the first polarizer axis so as to define an angle θ1 therebetween; f) orienting an optical axis of the second retardation film relative to the second polarizer axis so as to define an angle θ2 therebetween; g) selecting values for the θ1 and θ2 so as to center the highest contrast viewing zone of the display at a point substantially below the 0° vertical viewing angle axis, thereby positioning and centering the highest contrast viewing zone substantially distant from an inversion area located above the 0° vertical viewing axis.

In certain further preferred embodiments of this invention, the angles θ1 and θ2 are selected to be in the range of from about 3°–5°.

In certain further preferred embodiments of this invention, the angles θ1 and θ2 are selected to be in the range of from about 2°–10°.

In still further preferred embodiments of this invention, the retardation films are uniaxial and have negative birefringence.

In still other preferred embodiments of this invention, the retardation films are biaxial and are either positively or negatively birefringent.

This invention further fulfills the above described needs in the art by providing a pixel for a twisted nematic liquid crystal display, comprising: a rear, light-entrance polarizer having a transmission axis oriented in a first direction; a front, light exit polarizer having a transmission axis oriented in a second direction wherein said first and second directions are substantially perpendicular to one another thereby defining a normally white display; a rear biaxial retardation film disposed between said rear polarizer and a twisted nematic liquid crystal material, wherein the liquid crystal material twists at least one wavelength of normally incident visible light about 80°–100° as it passes therethrough; a front biaxial retardation film disposed between the front polarizer and the liquid crystal material; wherein the rear retardation film optical axis having the largest index of refraction is oriented in a direction substantially parallel to the first direction of the transmission axis of the rear polarizer, and the front retardation film optical axis having the largest index of refraction is oriented substantially parallel to the second direction of the transmission axis of the front polarizer; and wherein the optical axes of the rear and front retardation films with said largest indices of refraction each have retardation values ($d \cdot \Delta_{zx}$) in the range of from about −100 to −200 nm such that the viewing zone of the pixel has high contrast ratios at large predetermined horizontal viewing angles.

This invention will now be described with respect to certain embodiments thereof, accompanied by certain illustrations, wherein:

IN THE DRAWINGS

FIG. 1 is a contrast ratio graph utilizing white light for a light valve liquid crystal pixel with a voltage of 6.8 volts applied thereto.

FIG. 2 is a contrast ratio curve graph using white light in the prior art light valve of FIG. 1.

FIG. 3 is an intensity versus driving voltage plot of the prior art light valve of FIGS. 1 and 2. This plot or graph illustrates a fairly large inversion hump over a wide range of horizontal viewing angles at driving voltages of about 3.2 volts and greater.

FIG. 4 is a schematic diagram of the optical components of a prior art "P-buffed" normally white twisted nematic liquid crystal display having retardation films with retardation values of at least 300 nm.

FIGS. 5A–5D are specific wavelength contrast curve diagrams or graphs showing viewing angle characteristics of the prior art normally white liquid crystal display of FIG. 4.

Each of the FIGS. 5A–5D represent different orientations of the optical axes of the front and rear polarizers of the FIG. 4 normally white display.

FIG. 6 is a graph illustrating the angular relationship between the horizontal and vertical viewing angles discussed herein, and their relationship with the conventional liquid crystal display angles ϕ and θ.

FIG. 7 is a computer simulation contrast ratio curve graph of a normally white liquid crystal display having front and rear retardation films with retardation values of 320 nm. The display simulated by FIGS. 7–10 is not prior art to the present invention, but is merely used for the purpose of later comparison to certain embodiments of this invention.

FIG. 8 is a computer simulation contrast ratio graph of the display of FIG. 7 wherein 5.0 volts are applied across the display and the 630 nm wavelength is used.

FIG. 9 is a computer simulation contrast ratio curve graph of the display of FIGS. 7–8 using a green wavelength of 550 nm and applying a voltage of 6.8 volts across the liquid crystal material.

FIG. 10 is a computer simulation contrast ratio curve graph of the display of FIGS. 7–9 using a blue wavelength of 480 nm and applying 6.8 volts across the liquid crystal material.

FIG. 11(*a*) is a schematic diagram of the optical components of a first embodiment of a normally white twisted nematic liquid crystal display of this invention.

FIG. 11(*b*) illustrates the angular relationships between the respective optical axes of the first embodiment of this invention.

FIG. 11(*c*) illustrates the angular relationships of another embodiment of this invention as viewed from the point of view of an observer or viewer of the display.

FIG. 12 is a computer simulation contrast ratio curve graph illustrating the contrast ratios of the first embodiment of this invention when 6.8 volts is applied across the liquid crystal material, 120 nm retarders are used, and the red wavelength of 630 nm is used.

FIG. 13 is a computer simulation contrast ratio curve graph of the first embodiment to this invention when 6.0 volts is applied across the liquid crystal material, 120 nm retarders are used, and the red wavelength of 630 nm is used.

FIG. 14 is a computer simulation contrast ratio graph of a display according to the first embodiment of this invention when a green wavelength of 550 nm is used, 120 nm retarders are used, and 6.8 volts is applied across the liquid crystal material.

FIG. 15 is a computer simulation contrast ratio curve graph of the display according to the first embodiment of this invention using a green wavelength of 550 nm when 6.0 volts is applied across the liquid crystal material and 120 nm retarders are used.

FIG. 16 is a computer simulation graph illustrating the contrast ratio curves of the display according to the first embodiment of this invention when a blue wavelength of 480 nm is used and 6.8 volts is applied across the liquid crystal material the rear and front retardation films have retardation values of 120 nm.

FIG. 17 is a computer simulation contrast ratio curve graph illustrating the contrast ratios of a display according to the first embodiment of this invention when a blue wavelength of 480 nm is used, 120 nm retarders are used, and 6.0 volts is applied across the liquid crystal material.

FIG. 18 is a computer simulation transmission versus driving voltage plot of horizontal viewing angles for the first embodiment of this invention when the rear and front retardation films have retardation values of 120 nm.

FIG. 19 is a computer simulation transmission versus driving voltage plot of vertical viewing angles for the first embodiment of this invention when the rear and front retardation films have retardation values of 120 nm using white light.

FIG. 20 is a computer simulation contrast ratio curve graph of the first embodiment of this invention when a red wavelength of 630 nm is used, 160 nm retarders are used, and 6.8 volts is applied across the liquid crystal material.

FIG. 21 is a computer simulation contrast ratio curve graph for the first embodiment of this invention when a green wavelength of 550 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 160 nm.

FIG. 22 is a computer simulation contrast ratio curve graph of the first embodiment of this invention when a blue wavelength of 480 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 160 nm.

FIG. 23 is a computer simulation contrast ratio curve graph for the first embodiment of this invention when a red wavelength of 630 nm is used, 6.8 volts is applied across the liquid crystal material, and the front and rear retardation films have retardation values of 80 nm.

FIG. 24 is a computer simulation contrast ratio curve graph for the first embodiment of this invention when a green wavelength of 550 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 80 nm.

FIG. 25 is a computer simulation contrast ratio curve graph of the first embodiment to this invention when a blue wavelength of 480 nm is used, 6.8 volts is applied across the liquid crystal material, and the rear and front retardation films have retardation values of 80 nm.

FIG. 26 is a white light measured contrast ratio curve graph of a light valve according to the first embodiment of this invention which utilized uniaxial and positively birefringent rear and front retardation values of 120 nm, and 6.8 volts was applied to the light valve.

FIG. 27 is a white light measured contrast ratio curve graph of the light valve of FIG. 26 when 6.0 volts was applied to the light valve and uniaxial and positively birefringent rear and front 120 nm retarders were used.

FIG. 28 is a white light measured contrast ratio curve graph of the light valve of FIG. 26 when 5.0 volts was applied thereto, and uniaxial and positively birefringent rear and front 120 nm retarders were used.

FIG. 29 is a white light measured contrast ratio curve graph of the light valve of FIG. 26 when 4.0 volts was applied thereto, and uniaxial and positively birefringent rear and front 120 nm retardation values were used.

FIG. 30 is a white light measured intensity versus driving voltage plot of the light valve of FIG. 26 when rear and front uniaxial and positively birefringent 120 nm retardation films were used. The plot illustrates the gray level behavior of the light valve pixel at a plurality of horizontal viewing angles along the 0° vertical viewing axis.

FIG. 31 is a white light measured contrast ratio curve graph for a normally white liquid crystal display according to the first embodiment of this invention when rear and front 120 nm retardation films were used and 6.8 volts was applied to the display.

FIG. 32 is a white light measured contrast ratio curve graph of the liquid crystal display of FIG. 31 when rear and

front 120 nm retardation films were used and 6.0 volts was applied to the display.

FIG. 33 is a white light measured contrast ratio curve graph of the liquid crystal display of FIG. 31 when rear and front 120 nm retardation films were used and 5.0 volts was applied to the display.

FIG. 34 is a measured contrast ratio curve graph for the normally white liquid crystal display of FIG. 31 when 4.0 volts was applied to the display, white light was used, and the rear and front retardation films were uniaxial and had retardation values of 120 nm.

FIG. 35 is a measured intensity versus driving voltage plot showing the results for various horizontal angles along the 0° vertical viewing axis for the normally white liquid crystal display of FIG. 31 when white light was used, and the rear and front retardation values were 120 nm.

FIG. 36 is a measured contrast ratio curve graph of a liquid crystal display according to the first embodiment of this invention wherein white light was utilized, 120 nm retarders were used, and 6.0 volts was applied to the display.

FIG. 37 is a measured contrast ratio curve of a light valve according to another embodiment of this invention wherein white light was used, 6.8 volts was applied to the pixel, the retardation films values were 120 nm, and the retardation films were rotated −8° symmetrically.

FIG. 38A is a measured contrast ratio curve of the light valve of FIG. 37 when 5.0 V was applied to the light valve.

FIG. 38B is a white light measured intensity versus voltage graph for the light valve of FIGS. 37 and 38A.

FIG. 39 is a measured contrast ratio curve of a liquid crystal display according to this invention wherein white light was used, 120 nm retardation films were used, 6.0 volts was applied to the display, and the retardation films were rotated −3° symmetrically, and the cell gap "d" was about 5.1 μm in the red subpixel and about 5.7 μm in the green and blue subpixels due to color filter thicknesses.

FIG. 40 is a computer simulation contrast ratio curve graph of a normally white liquid crystal display according to another embodiment of this invention wherein the retardation films are rotated +4° symmetrically, 160 nm retardation films are used, a green 550 nm wavelength is used, and 6.8 V is applied.

FIG. 41 is a cross-sectional view of a liquid crystal display pixel according to certain embodiments of this invention.

FIG. 42 is a partial cut-away view illustrating an active matrix liquid crystal display including a plurality of pixels according to certain embodiments of this invention.

FIG. 43 is a computer simulation contrast ratio curve graph of an LCD according to another embodiment of this invention wherein the rear and front retardation films are uniaxial, but have negative birefringent values. The rear and front retardation films of this embodiment both have retardation values of $\Delta_{ZX}=\Delta_{ZY}=-160$ nm where $\Delta_{ZX}=d\cdot(n_Z-n_X)$, where "n" is the index of refraction and "d" is the thickness of the film. Therefore, the optical axes of these films are oriented in the "Z" direction.

FIG. 44 is a computer simulation contrast ratio curve graph of an LCD according to yet another embodiment of this invention where the LCD has a cell gap of 5.7 μm, 6.0 V is applied, and the rear and front retardation films are biaxial with negative retardation values. The rear and front films of this embodiment have retardation values Δ_{ZX} and Δ_{ZY} of −160 nm and −60 nm respectively. A 550 nm wavelength was used in this graph.

FIG. 45 is a measured contrast ratio graph of a light valve pixel according to another embodiment of this invention where 6.0 V was applied, biaxial rear and front retardation films obtained from Allied Signal Corporation were used, and the light valve was "X-buffed."

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS OF THIS INVENTION

FIG. 11(*a*) is a schematic view of the optical components and their respective orientations of a first embodiment of this invention. As shown in FIG. 11(*a*) the normally white "X-buffed" LCD (or pixel) of this embodiment discloses a rear linear polarizer 1 provided at the light incident side of the liquid crystal layer 5, an exit or front linear polarizer 9 provided at the light exit side of the liquid crystal layer 5, a rear retardation film or plate 3 provided between the liquid crystal layer and the rear polarizer 1, and a front retardation film or plate 7 provided between the liquid crystal layer 5 and the front linear polarizer 9. The retardation films of this embodiment preferably are uniaxial and have positive birefringent (ΔN) values. As example of uniaxial positively birefringent retardation films useful in the practice of this invention are films commercially available from, for example, Nitto Corp., Japan, or Nitto Denko America, Inc., New Brunswick, N.J. as Model No. NRF-RF120 (120 nm retarder).

In addition, biaxial retardation films are obtainable, for example, from Allied Signal Corporation, and negatively birefringent uniaxial/biaxial soluble polyimide retardation films are obtainable from the University of Akron and may also be used in certain embodiments of this invention.

Normally incident light 11 is directed toward the rear linear polarizer 1 from a conventional backlighting system such as is disclosed, for example, in U.S. Pat. No. 5,161,041. The liquid crystal material 5 is preferably of the twisted nematic type and twists at least one normally incident visible wavelength of light about 80°–100° (most preferably about 90°) as it passes through the liquid crystal layer 5. The amount of twist provided by the liquid crystal layer depends upon: the wavelength of light propagating therethrough, the thickness "d" of the liquid crystal layer 5, the birefringence of the liquid crystal layer, and the orientation of the rear and front buffing zones. The liquid crystal material or layer is preferably about 4.5–6.0 μm thick and has a birefringent value of 0.084 at room temperature.

Between the rear retardation film 3 and the liquid crystal layer 5 is a rear orientation film 21 which has an orientation axis or buffing zone oriented in a direction B_1. The rear orientation film 21 oriented in direction B_1 acts to align the liquid crystal layer molecules adjacent the rear orientation film in this direction B_1. The display of FIG. 11(*a*) is also provided with a front orientation film 22 or buffing zone having an orientation direction B_2. The direction B_2 of the front orientation film is preferably substantially perpendicular to direction B_1 of the rear orientation film. As is the case with the rear orientation film, the purpose of the front orientation film is to align the liquid crystal molecules along the interface between the liquid crystal layer 5 and the front orientation film in direction B_2. As described hereinafter more fully, the rear orientation direction B_1 is aligned from the lower right to the upper left, and the front orientation direction B_2 is oriented from the upper right to the lower left which are not to be confused with the directions of the buffing in U.S. Pat. No. 5,184,236 shown in FIG. 4 herein. The effect of the alignment of these two orientation films is to provide for a liquid crystal layer twist of about 80°–100° (most preferably about 90°).

The rear linear polarizer 1 is arranged so that its transmission axis P_R is substantially parallel with the orientation or buffing direction B_2 of the front orientation film. The front or exit linear polarizer 9 is arranged so that its transmission axis P_F is substantially perpendicular to the transmission axis P_R of the rear linear polarizer 1. Because the transmission axis P_R of the rear linear polarizer 1 is substantially perpendicular to the orientation or buffing direction B_1 of its adjacent orientation film 21, this defines what is meant by "crossed" buffing (i.e. "X-buffed"). "P" (i.e. parallel) buffing simply means that the direction of buffing of the buffing film adjacent its respective polarizer is parallel to the direction of polarization. This arrangement of the transmission axes of the rear and front polarizers also defines a twisted nematic normally white liquid crystal display cell in that as light exits the front linear polarizer 9, it may be viewed by a viewer or observer 15 when the display is in the OFF state.

This embodiment utilizes an "X-buffed" optical arrangement because such an arrangement provides superior results with respect to a "P-buffed" orientation. However, a "P-buffed" arrangement could also be used in certain other embodiments of this invention.

The rear retardation film 3, which is preferably but not necessarily of the uniaxial type, has its optical axis R_R arranged in a direction substantially parallel to the transmission axis P_R of the rear linear polarizer 1. Also, the optical axis R_R of the rear retardation film is arranged in a direction substantially perpendicular to the direction B_1 of the rear orientation film. The retardation value ($d \cdot \Delta N$) of the rear retardation film 3 is preferably in the range of about 80–200 nm, more preferably about 100–160 nm, and most preferably about 120–140 nm.

The front and rear retardation films are preferably positioned about equal distances away from the liquid crystal material in this and certain other embodiments of this invention.

The front retardation film 7, which is located on the opposite side of the liquid crystal layer 5 as the rear retardation film 3, is also preferably uniaxial. The optical axis R_F of the front retardation film 7 is preferably oriented in a direction substantially parallel to the transmission axis P_F of the front or exit linear polarizer 9. Also, the optical axis R_F of the front retardation film 7 is preferably oriented in a direction substantially perpendicular to the orientation direction B_2 of the front orientation film. The terms "substantially parallel" and "substantially perpendicular" when used herein but only as used to define the orientation of the optical axes of the rear and front retardation films, means that the axes of the retardation films are arranged in such a manner ± about 10° unless otherwise specified.

The retardation value of the front retardation film 7 is preferably the same as that of the rear retardation film 3. In other words, the retardation value ($d \cdot \Delta N$) of the front retardation film 7 is in the range of about 80–200 nm, more preferably about 100–160 nm and most preferably about 120–140 nm.

The advantages of utilizing about 80–200 nm retardation films according to the teachings of this invention include a resulting larger viewing zone, and the ability to shift the viewing zone vertically away from an inversion area without substantially distorting the viewing zone.

Also, the retardation values of the rear and front retardation films are preferably about the same so as to define a viewing zone substantially symmetrical about the 0° horizontal viewing axis. The greater the difference between the retardation values of the retardation films 3 and 7, the greater the loss of symmetry of the viewing zone about the 0° horizontal viewing axis. This may be desireable in certain embodiments of this invention.

Normally incident white light 11 from a conventional backlighting system is directed towards the normally white liquid crystal display shown by FIG. 11(a) and toward the rear linear polarizer 1 and its transmission axis P_R. The rear linear polarizer 1 linearly polarizes the normally incident white light 11 in a direction P_R. After being polarized by the polarizer 1, the light then proceeds toward and through the rear retardation film 3 which has a specific retardation value in the range of about 80–200 nm. After being transmitted through the rear retardation film 3 and being affected by its optical axis R_R, the white light then proceeds through the rear buffing or orientation film having an orientation direction B_1 and into the liquid crystal material 5. When proceeding through the liquid crystal material 5, the twisted nematic material twists the normally incident white light about 80°–100°, most preferably about 90°.

After exiting the liquid crystal layer 5 (with its molecules aligned along the front surface thereof in direction B_2), the light proceeds through color filters (not shown) and into and through the front retardation film 7. The color filters, may, for example, be red, green, blue, white, or combinations thereof as shown and discussed, for example, in U.S. Pat. No. 4,632,514, the disclosure of which is incorporated herein by reference. After proceeding through the front retardation film 7 and being affected by its optical axis R_F, the color filtered light approaches the front polarizer 9. When the liquid crystal display is in the unenergized or OFF state (no voltage above V_{th}, the threshold voltage, is applied across the liquid crystal material) the twisted light proceeds through the front polarizer 9 and the display appears bright, white, or colored. When the display is in its energized or ON state (a voltage greater than V_{th} is applied across the liquid crystal material) the light is substantially blocked to a voltage dependent extent by the front polarizer 9 and the display appears darkened to a viewer.

Electrodes provided on each side of the liquid crystal material are conventional in the art and are not shown in the drawings of FIGS. 11(a)–11(c) for the purpose of simplicity.

FIG. 11(b) illustrates the angular relationship between the respective axes of the polarizers, retardation films, and orientation films of the first embodiment of this invention. FIGS. 11(b) and 11(c) are perspective views from the viewer side of the liquid crystal display. As shown in FIG. 11(b), the transmission axis P_F of the front polarizer, the optical axis R_F of the front retardation film, and the orientation direction B_1 of the rear orientation film are about parallel one to the others. Also, the transmission axis P_R of the rear polarizer, the optical axis R_R of the rear retardation film, and the direction B_2 of the front orientation film are also about parallel one to the others. Therefore, an angle of about 90° is defined between the orientations of these two groups of directions as shown in FIG. 11(b). Preferably, the angular arrangement shown in 11(b) of the first embodiment of this invention provides for a viewing zone substantially symmetrical about the 0° vertical viewing axis or reader.

The +X and +Y directions are illustrated in FIGS. 11(b) and 11(c), and the +Z direction comes out of the figures toward the viewer or reader.

FIG. 11(c) is a perspective view illustrating the angular relationship between the above discussed optical directions in another embodiment of this invention. In this embodiment, the optical axes of the rear and front retardation films 3 and 7 are symmetrically rotated negatively so as

to shift the central location of the displays' viewing zone to a position below the 0° vertical viewing axis while substantially preserving its shape. This embodiment of this invention illustrated by FIG. 11(c) utilizes the same parameters as those described with respect to the first embodiment of this invention except for the orientations of the optical axes of the retardation films. As in the first embodiment of this invention, the transmission axes P_F and P_R of the front and rear linear polarizers in this embodiment define an angle of about 90° therebetween. Also, the directions B_1 and B_2 are substantially perpendicular to one another and are about parallel with the transmission axes P_F and P_R of the front and rear polarizers respectively.

The difference between the first embodiment and this embodiment is that in this embodiment shown in FIG. 11(c) the optical axis R_R of the rear retardation film is rotated so as to define an angle θ1 between the transmission axis of the rear polarizer and the optical axis R_R of the rear retardation film. Also, the optical axis R_F of the front retardation film in this embodiment is rotated so as to define an angle θ2 between the transmission axis P_F of the front polarizer and the optical axis R_F of the front retardation film.

As illustrated in FIG. 11(c), the optical axis R_R of the rear retardation film is rotated clockwise relative to directions P_R and B_2, while the optical axis R_F of the front retardation film is rotated counterclockwise relative to directions P_F and B_1. Preferably, the angles θ1 and θ2 as shown in FIG. 11(c) are substantially equal to one another thereby defining a viewing zone for the normally white display which is substantially symmetrical about the 0° horizontal viewing axis. Because the optical axis R_F of the front retardation film has been rotated counterclockwise and the optical axis R_R of the rear retardation film has been rotated clockwise to substantially equal extents, the display of this embodiment is said to have its retardation films rotated negatively in a symmetrical manner. The term "symmetrical" means that the angles θ1 and θ2 are substantially equal to one another. For example, if the normally white display illustrated by FIG. 11(c) were to have its rear and front retardation film axes "rotated −8° symmetrically," the angles θ1 and θ2 each would be about 4° respectively. Therefore, the angle δ between directions R_R and R_F would be about 82° when the retardation films of this embodiment were rotated −8° symmetrically. It should then be clear that if the optical axes of the rear and front retardation films were to be rotated −4° symmetrically, the angles θ1 and θ2 would each be about 2°, and the angle δ between the optical axes of the rear and front retardation films would be about 86°.

The purpose of rotating the optical axes R_R and R_F of the rear and front retardation films is to shift the central location of the viewing zone vertically while still substantially maintaining its shape. In the liquid crystal display art, different customers often desire different viewing characteristics such as the position of the viewing zone. Because of different requirements for different customers, it is advantageous to have a display which may have its viewing zone shifted vertically in accordance with a customer's needs simply by rotating the optical axes of the rear and front retardation films. By rotating the optical axes R_R and R_F of the retardation films to a predetermined negative extent symmetrically, the viewing zone, while being substantially maintained with respect to shape, is shifted to a position centered substantially below the 0° vertical viewing axis and, therefore, away from the inversion zones present above the 0° vertical viewing axis. Such shifts with respect to viewing zones are discussed and shown graphically below with reference to this and other embodiments of this invention.

Another embodiment of this invention which is related to the embodiment disclosed in FIG. 11(c) is the situation where the optical axes of the rear and front retardation films are rotated to a predetermined positive value symmetrically. When the optical axes R_R and R_F are rotated, for example, +6° symmetrically, the optical axis R_R is rotated 3° counterclockwise relative to directions P_R and B_2, while retardation axis R_F is rotated 3° clockwise relative to directions B_1 and P_F. Therefore, the rear and front retardation optical axes R_R and R_F define angles θ1 and θ2 of about 3° between their axes and the transmission axes of their respective adjacent polarizers. In this situation where the optical axes R_R and R_F are rotated +6° symmetrically, the angle δ is about 96°. When the optical axes of the retardation films are rotated in a positive manner symmetrically, the result is a shifting of the viewing zone to a position centered substantially above the 0° vertical viewing axis.

FIGS. 12–25 are computer simulations of the first embodiment of this invention illustrating the effect of different driving voltages, retardation values, and wavelengths.

FIGS. 12 and 13 are computer simulation contrast ratio curve graphs of the first embodiment of this invention when the red wavelength of 630 nm is used. With respect to FIGS. 12 and 13, the cell gap "d" is 5.70 μm, and the optical axes R_R and R_F of the rear and front retardation films are parallel to the transmission axes of the rear and front linear polarizers respectively. The rear and front retardation films 3 and 7 each have retardation values of 120 nm in the computer simulation graphs of these Figures, as well as FIGS. 14–19.

In FIG. 12, V_{ON} was 6.8 volts and V_{OFF} was 0.9 volts. As can be seen in FIG. 12, the contrast ratios of the red wavelength are extremely good, especially horizontally. The 30:1 contrast ratio curve extends off the graph in both horizontal directions, while the 10:1 contrast ratio curve extends off the graph in the positive vertical direction. The 30:1 contrast ratio curve extends along the 0° vertical viewing axis a total of about 110° from about −55° to +55° horizontal. Furthermore, the 50:1 contrast ratio curve along the 0° vertical viewing axis extends from about −46° to +46°. These are significant improvements over the prior art.

FIG. 13 is a contrast ratio curve graph which used as parameters those described above with respect to FIG. 12 except that V_{ON} was 6.0 volts. As can be seen in FIG. 13, by lowering the parameter V_{ON} or driving voltage, the viewing zone is diminished vertically and is slightly shifted upward in the positive vertical viewing direction. However, when, in FIG. 13, the driving voltage is 6.0 volts, the 50:1 contrast ratio curve extends along the 0° vertical viewing axis to extents of about ±55° horizontal.

FIGS. 14–15 are computer simulation contrast (or contour) ratio curve graphs utilizing the green wavelength of 550 nm in the display of the first embodiment of this invention. The cell gap "d" with respect to FIGS. 14–15 was 5.70 μm and the rear and front retardation films 3 and 7 had retardation values of 120 nm. FIG. 14 illustrates the case where V_{ON} was 6.8 volts while FIG. 15 had a V_{ON} of 6.0 volts. As shown in FIG. 14, the 50:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis a total of about 90° from horizontal angles of about −45° to +45°. As can be seen in FIG. 15, by decreasing the driving voltage the viewing zone is constricted slightly vertically and is shifted upward to a position centered substantially above the 0° vertical viewing axis.

FIGS. 16–17 are computer simulation contrast ratio curves of the first embodiment of this invention when the blue wavelength of 480 nm was used and the rear and front

retardation films had retardation values of 120 nm. In FIGS. 16–17, the cell gap was also 5.70 μm. As was the case with respect to the red and green wavelengths, when V_{ON} is decreased from 6.8 volts (FIG. 16) to 6.0 volts (FIG. 17), the viewing zone shifts upward substantially above the 0° vertical viewing axis and shrinks vertically with respect to the overall vertical angles covered by the 10:1 contrast ratio curve.

FIG. 18 is a driving voltage versus transmission graph illustrating the transmission at various driving voltages in a range of horizontal viewing angles (−60° to 60°) along the 0° vertical viewing axis. With the exception of the ±60° curves, there is substantially no effect of inversion upon these transmission versus driving voltage curves throughout the gray level driving voltage zones of about 2–6 volts. In other words, throughout the gray level driving voltage zones, when the driving voltage is increased, the transmission is decreased accordingly, thus, providing for good gray level performance along the 0° vertical viewing axis throughout the horizontal angles shown and defined in FIG. 18. One needs simply to compare the graph of FIG. 18 with the graph of prior art FIG. 3 to see that the arrangements of the optical parameters of the first embodiment of this invention decrease the effect of inversion upon various horizontal viewing angles and provide for an improved gray level performing NW liquid crystal display.

The curves of FIG. 19 representing different vertical viewing angles along the 0° horizontal viewing axis have transmission percentages which generally diminish with increases in driving voltage, possibly with the exception of the +40° vertical viewing angle. The effect of inversion is only seen with respect to the vertical viewing angles of +30° to +40°. In other words, throughout a wide range of gray level driving voltages, when the voltage is increased the transmission is decreased accordingly thus providing for excellent gray level performance throughout the vertical range. The cell gap in FIGS. 18–19 was 5.70 μm. It is noted that white light was used in plotting the driving voltage versus transmission curves of FIG. 18 and FIG. 3. The large inversion humps present in FIG. 3 do not appear in FIGS. 18–19, thus, illustrating an improvement of this embodiment over the prior art.

FIGS. 20–22 are computer simulation contrast ratio curve graphs of the first embodiment of this invention when the rear and front retardation films 3 and 7 had retardation values of 160 nm, V_{ON} was 6.8 volts, and the cell gap "d" was 5.70 μm.

FIG. 20 illustrates the case where the red wavelength of 630 nm was used. In comparing the case where the LCD of the first embodiment utilized 160 nm retardation films (FIG. 20) with the case where 120 nm retardation films (FIG. 12) were used, the difference is that when rear and front retardation values of 120 nm were used the contrast ratios extended to further extents in both the horizontal and vertical directions. For example, with respect to the red wavelength of 630 nm shown in FIG. 12 (120 nm retardation films) and FIG. 20 (160 nm retardation films) the 50:1 contrast ratio curve in FIG. 12 extended horizontally a total of about 110° from about −55° horizontal to about +55° horizontal, while in contrast to this, 50:1 contrast ratio curve in the 160 nm case (FIG. 20) extended horizontally to angles of about ±45°. However, the boomerang shape of the viewing zone shown in FIG. 12 was substantially eliminated when the 160 nm retardation films were used as shown in FIG. 20. Also, the 30:1 contrast ratio curve in FIG. 20 extended in some places to extents further than that of the 30:1 curve of FIG. 12. In sum, both cases, one with retardation films of 120 nm and the other with retardation films of 160 nm, exhibited excellent results in that their respective viewing zones extended to large horizontal and vertical viewing angles.

FIG. 21 illustrates the case where the green wavelength of 550 nm was used in the first embodiment of this invention and the rear and front retardation films 3 and 7 had retardation values of 160 nm. This graph shows that the use of 160 nm retardation films in the first embodiment of this invention provided a viewing zone which extended to large viewing angles in both the horizontal and vertical directions.

FIG. 22 illustrates the case where the blue wavelength of 480 nm was used in combination with 160 nm retardation films. In the cases where 160 nm retardation films were used, the viewing zones were diminished slightly with respect to the 120 nm cases, however, the contrast ratio curves are still excellent.

FIGS. 23–25 are computer simulation contrast ratio curve graphs of the first embodiment of this invention when the rear and front retardation films 3 and 7 had retardation values of 80 nm, V_{ON} was 6.8 volts, and the cell gap "d" was 5.70 μm. FIG. 23 illustrates the case where a red wavelength of 630 nm was used. FIG. 24 illustrates the case where the green wavelength of 550 nm was used, and FIG. 25 illustrates the case where the blue wavelength of 480 nm was used. FIGS. 23–25 all represent excellent contrast ratio curves for the first embodiment of this invention when retardation values of 80 nm were used. The displays of FIGS. 12–25 all utilized uniaxial positively birefringent retardation films.

This invention will now be described with respect to certain examples as follows:

EXAMPLE 1

In this first example, an "X-buffed" light valve having a cell gap "d" of 5.86 μm and a liquid crystal birefringence (ΔN) of 0.084 at room temperature was manufactured and tested as follows. The liquid crystal material used is available commercially from E. Merck Ltd. or its U.S. representative EM Industries, Inc., Hawthorne, N.Y. as Model No. ZLI4718. Data resulting from the light valve of this example is illustrated in FIGS. 26–30.

The light valve pixel of this example was similar to the first embodiment of this invention in that the rear linear polarizer had a transmission axis direction about parallel to the optical axis of the rear retardation film, and the optical axis of the front retardation film was about parallel to the transmission axis of the front or exit linear polarizer. The orientation or buffing direction of the rear orientation film was approximately perpendicular to the optical axis of the rear retardation film, and was approximately parallel to the optical axis of the front retardation film. The optical axes of the rear and front retardation films defined an angle δ of about 90° therebetween. The orientation direction of the front orientation film was approximately parallel to the direction of the optical axis of the rear retardation film, and was substantially perpendicular to the direction of the rear orientation film. White light (RGB tri-peaked) was used when testing the light valve of this example (see FIGS. 26–30). The rear and front retardation films were of the uniaxial type and had positive birefringent values. Also, the rear and front retardation films both had retardation values of 120 nm. The temperature was about 35°–40° C.

FIG. 26 illustrates the experimental data when the driving voltage V_{ON} was 6.8 volts and V_{OFF} was 0.2 volts for this example. As can be seen, the 10:1 contrast ratio curve

extends horizontally along the 0° vertical viewing axis to about ±50° horizontal thereby defining a total horizontal viewing range along the 0° vertical viewing axis of about 100°. This 100° range is to be compared with the about 77° range shown in prior art FIG. 1, and the about 65° horizontal range shown in prior art FIG. 5D. In other words, the 10:1 contrast ratio curve of this example at 6.8 volts is substantially improved over displays and light valves of the prior art. In this respect, it is also to be noted that the 50:1 contrast ratio curve shown in FIG. 26 extends along the 0° vertical viewing axis a substantial distance, i.e. over a total angular span of about 75°.

FIG. 27 illustrates the case where V_{ON} was 6.0 volts for the normally white light valve of this first example. When V_{ON} is decreased from 6.8 volts to 6.0 volts, a more realistic V_{ON} was applied to the pixel and the 10:1 contrast ratio curve extended horizontally slightly further than that shown in FIG. 26.

FIG. 28 illustrates the case where V_{ON} was decreased to 5.0 volts for the light valve of this first example. In the case where 5.0 volts was applied to the pixel, the 10:1 contrast ratio curve defines a range of about 112° along the 0° vertical viewing axis. This is significantly greater than the range defined by the 10:1 contrast ratio curves of the prior art described and illustrated herein.

FIG. 29 illustrates the case where V_{ON} was 4.0 volts for the light valve of this first example. When 4.0 volts was applied to the pixel the 10:1 contrast ratio curve substantially extends off the graph in both horizontal directions. However, when the voltage is decreased, as is the case in FIG. 29, the viewing zone shrinks vertically and is shifted slightly upward, a condition generally true with regard to each of the illustrated decreases in voltage.

FIG. 30 is an intensity versus driving voltage plot for this example illustrating the effects of gray level driving voltages for different horizontal viewing angles ranging from −60° to +60° along the 0° vertical viewing axis. As can be seen in FIG. 30, the gray level performance of this pixel is very good in that the inversion humps are relatively small or non-existent for a wide range of horizontal viewing angles defined herein. In other words, the horizontal gray level performance of this light valve is good because as the driving voltage increases, the intensity for the most part decreases accordingly. Therefore, when the driving voltage of this pixel is increased from one gray level voltage to another the intensity of the pixel generally decreases. The improved results illustrated in the graph shown in FIG. 30 are to be compared to the inferior results illustrated in the prior art graph, FIG. 3, where the inversion humps which begin at about 3.2 volts are relatively large and extend up into the range substantially over 200 fL. In short, the gray level characteristics of the light valve of this example are significantly improved over those of the prior art.

EXAMPLE 2

In this second example, a multi-colored liquid crystal display utilizing TFTs as switching devices in an active matrix array was constructed as follows. The normally white "X-buffed" liquid crystal display had a cell gap "d" of about 5.1 μm for the red subpixel which included a red color filter, and a cell gap "d" of about 5.7 μm for the green and blue subpixels which included green and blue color filters respectively. The difference in cell gap for the different subpixels was due to the different thicknesses of the color filters. The birefringence of the LC material was 0.084 at room temperature. The liquid crystal material was purchased from Merck, Model No. ZLI4718. The display had a rear linear polarizer having a transmission axis substantially perpendicular to the transmission axis of the front or exit linear polarizer. A rear retardation film having an optical axis about parallel to the transmission axis of the rear polarizer was sandwiched between the rear polarizer and the liquid crystal material. Likewise, a front retardation film having an optical axis about parallel to the transmission axis of the front polarizer was disposed between the front polarizer and the liquid crystal material. A rear orientation film was provided with an orientation direction about perpendicular to the optical axis of the rear retardation film, and about parallel to the transmission axis of the front polarizer. A front orientation film was provided with an orientation direction substantially parallel to the transmission axis of the rear polarizer, and about perpendicular to the optical axis of the front retardation film.

The optical axes of the rear and front retardation films defined an angle δ of about 90° therebetween. The rear and front retardation films both had retardation values of 120 nm. The front and rear retardation films both had positive birefringent values and were of the uniaxial type purchased from Nitto Denko America Corporation, New Brunswick, N.J. White light was used in testing this display and the measured results are reported in FIGS. 31–35.

FIG. 31 illustrates the contrast ratio curves when a V_{ON} of 6.8 volts was applied to this normally white liquid crystal display. As can be seen, the 10:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis a total of at least about 120°. This range is significantly greater than the ranges defined by the 10:1 contrast ratio curves of the prior art discussed above. Likewise, the 30:1 contrast ratio curve of FIG. 31 extends along the 0° vertical viewing axis to horizontal angles of about ±42° horizontal. The 10:1 contrast ratio curve of this example when 6.8 volts was applied to the display extends vertically along the 0° horizontal viewing axis from about −40° to about +35° vertical. Again, this range defined vertically by the 10:1 contrast ratio curve of this example is significantly improved over that of the prior art.

FIG. 32 illustrates the situation where 6.0 volts was applied to the normally white liquid crystal display of this example. As can be seen in FIG. 32, when 120 nm retardation films are used and 6.0 volts is applied to the display, the 10:1 contrast ratio curve still extends at least a total of about 120° horizontally along the 0° vertical viewing axis. This liquid crystal display clearly exhibits excellent contrast ratio curves over very wide ranges of viewing angles.

FIG. 33 illustrates the situation where 5.0 volts was applied to the display of this example. As shown the 10:1 contrast ratio curve still extends at least a total of about 120° horizontally along the 0° vertical viewing axis when 5.0 volts was applied to the display. The viewing zone, as previously discussed, decreases vertically as the voltage drops.

FIG. 34 illustrates the situation where 4.0 volts was applied to the display of this example. Again, the 10:1 contrast ratio curves still extends off the graph horizontally along the 0° vertical viewing axis defining a range of at least about 120°. Taken together, FIGS. 31–34 illustrate that the inventive normally white display of this example, has excellent contrast ratios over a wide range of driving voltages, especially in the horizontal directions.

FIG. 35 is a driving voltages versus intensity plot for the display of this example when white light was used. This plot is for a range of horizontal viewing angles extending from

−60° to +60° along the 0° vertical viewing axis. As shown, there is virtually no inversion at any voltage for the various horizontal viewing angles defined therein. In other words, as the gray level or driving voltages increase, the intensity of light emitted from the display decreases in conjunction therewith, thus, providing excellent gray level performance for the display of this example. The plot of FIG. 35 when compared with that of FIG. 3 highlights how the LCDs of this invention virtually eliminate the inversion bumps experienced in the prior art, which allows the displays of this invention to be satisfactorily used throughout a wide range of gray level voltages.

EXAMPLE 3

An "X-buffed" normally white liquid crystal display was constructed having a cell gap of 5.1 μm for the red subpixel including a red color filter, and 5.7 μm for the green and blue subpixels including green and blue color filters respectively. The ΔN of the liquid crystal material was 0.084 at room temperature. The liquid crystal material was Merck's Mode No. ZLI4718. This liquid crystal display was driven by a conventional TFT active matrix array.

The normally white display included a rear polarizer, a rear retardation film, a rear substrate, a rear electrode, a rear orientation film, a liquid crystal layer, a front orientation film, a front electrode, a front substrate, a front retardation film, and a front or exit polarizer in that order. The transmission axis of the rear polarizer was approximately parallel to the optical axis of the rear retardation film and the orientation direction of the front orientation film. The transmission axis of the front polarizer was approximately parallel to the optical axis of the front retardation film and the orientation direction of the rear orientation film. The optical axes of the rear and front retardation films defined an angle of about 90° therebetween. The retardation values for both the rear and front films was 120 nm. The rear and front retardation films were of the uniaxial type and had positive birefringent values.

FIG. 36 illustrates the contrast ratio curves for this example when white light was applied to the display and a driving voltage of 6.0 volts was applied. As can be seen, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis to horizontal angles of at least about ±60°. Also, the 30:1 contrast ratio curve of this example when 6.0 volts was applied to the display extends along the 0° vertical viewing axis to horizontal angles of about ±44°. These are significant improvements over the prior art. Also, the 10:1 contrast ratio curve as shown in FIG. 36 extends along the 0° horizontal viewing axis to vertical angles of about ±33°. White light was used in obtaining the data generated by this graph.

EXAMPLE 4

In this example a normally white "X-buffed" light valve according to this invention was constructed wherein the optical axes of the rear and front retardation films were rotated −8° symmetrically thereby shifting the viewing zone to a position centered substantially below the 0° vertical viewing axis while maintaining its shape or integrity.

In this example, the light valve was constructed as follows. A rear linear polarizer was provided with a transmission axis P_R defining a first direction. A front linear polarizer was provided having a transmission axis P_F defining a second direction substantially perpendicular to the first direction. The orientation of the rear orientation film was substantially parallel to the second direction defined by the transmission axis P_F of the front polarizer. The orientation direction of the front orientation film was substantially parallel to the transmission axis direction defined by the transmission axis P_R of the rear polarizer.

A rear retardation film of the uniaxial type having a positive birefringent value was disposed between the rear polarizer and the rear orientation film. A front retardation film of the uniaxial type having a positive birefringent value was provided between the front polarizer and the front orientation film.

Because the optical axes of the rear and front retardation films were rotated −8° symmetrically, angles θ1 and θ2 were 4° respectively with an angle δ of 82° defining the angle between the optical axes of the rear and front retardation films. In other words, the optical axis R_F of the front retardation film was rotated 4° counterclockwise relative to the transmission axis P_F of the front polarizer. Also, the optical axis R_R of the rear retardation film was rotated clockwise 4° relative to the transmission axis P_R of the rear linear polarizer. Accordingly, the axes of the rear and front retardation films defined an angle of 82° therebetween represented by the angle δ in FIG. 11(*c*).

The rear and front retardation films of this example had retardation values of 120 nm. The liquid crystal material was Model No. ZLI4718 from E. Merck Ltd. The cell gap "d" of a liquid crystal layer was 5.86 μm for the light valve pixel of this example and the LC birefringence was 0.084. The temperature in this example, as in all of the other examples discussed herein, was about 35° C.–40° C. unless otherwise specified.

FIG. 37 is a contrast ratio curve graph illustrating the viewing zone of the light valve of this example when 6.8 volts and white light was applied thereto. As can be seen, the viewing zone is centered at a position about 10° below the 0° vertical viewing axis (i.e. at about the −10° vertical viewing axis) as a result of the −8° symmetrical rotation of the optical axes of the rear and front retardation films.

This example illustrates the situation where the viewing zone of a display or pixel is shifted to a position substantially below the 0° vertical viewing axis while still substantially maintaining the integrity or symmetry of the overall viewing zone. The symmetry of the viewing zone about the 0° horizontal viewing axis is substantially maintained because the rear and front retardation films had substantially equal retardation values.

FIG. 38A illustrates the viewing zone of the light valve of this example when 5.0 volts and white light was applied thereto. As can be seen in FIG. 38A, the viewing zone is still centered about the −10° vertical viewing axis and is provided with excellent contrast ratios at large viewing angles. As a result of the decrease on V_{ON} from 6.8 volts to 5.0 volts, it is seen in FIG. 38A that the viewing zone has been slightly constricted vertically and slightly expanded horizontally about the center of the viewing zone.

The advantage associated with the light valve of this example is that the centered position of the viewing zone of a given liquid crystal display or pixel thereof according to certain embodiments of this invention can be shifted vertically from one position to another while substantially maintaining the symmetry of the viewing zone in accordance with the specific needs of different customers. These shifts of the viewing zone are accomplished by simple rotation, preferably symmetrically, of the optical axes of the rear and front retardation films of certain embodiments of this invention.

FIG. 38B illustrates the inversion bump problem associated with the vertical viewing angles above the 0° vertical

viewing axis for the display of this example. The viewing zone of the display of this example is centered at a location below the 0° vertical viewing axis remote from these inversion areas illustrated in FIG. 38B. Thus, gray level performance is improved by centering the viewing zone at a position distant the inversion zone thereby limiting inversion effects to remote viewing angles.

EXAMPLE 5

A multi-colored normally white "X-buffed" liquid crystal display was constructed and tested with white light as follows. The display, including a conventional TFT matrix array, included a rear linear polarizer having a transmission axis defining a first direction, a front or exit linear polarizer having a transmission axis defining a second direction wherein the first and second directions were substantially perpendicular to one another, a rear retardation film between the rear polarizer and the liquid crystal layer and having an optical axis substantially parallel to the transmission axis of the rear polarizer, a front retardation film having an optical axis substantially parallel to the transmission axis of the front polarizer, a rear orientation film having an orientation direction substantially perpendicular to the first direction defined by the transmission axis of the rear polarizer, a front orientation film having an orientation direction substantially perpendicular to the transmission axis of the front polarizer, and finally a liquid crystal layer sandwiched between the orientation films. The rear and front retardation films had positive birefringent values and were of the uniaxial type. Furthermore, the rear and front retardation films each had a retardation value of 120 nm.

The optical axes of the rear and front retardation films were rotated −3° symmetrically. Therefore, with reference to FIG. 11(c), angles θ1 and θ2 were each 1.5°, and angle δ was 87° in the display of this example.

FIG. 39 is a white light contrast ratio curve graph showing the measured results when the liquid crystal display of this example had a voltage of 6.0 volts applied to the active matrix, V_{OFF} was 0.2 V, and V_{COM} was 8.14 V. The contrast ratios as shown in FIG. 39 are excellent in that the 10:1 contrast ratio curve extends significantly beyond a horizontal range of 120° along the 0° vertical axis. Furthermore, the 30:1 contrast ratio along the 0° vertical viewing axis defines a total range of about 100° which is significantly more than that of the prior art. The 10:1 contrast ratio curve in the vertical direction covers a range along the 0° horizontal viewing axis of between about −20° vertical and at least about 40° vertical.

As can be seen in FIG. 39, the −3° symmetrical rotation of the retardation films was not enough to shift the viewing zone below the 0° vertical viewing angle axis. This may be due to manufacturing derivations associated with certain optical elements of this display. Nevertheless, the viewing zone and contrast ratios are excellent, both horizontally and vertically.

The cell gap "d" of the display manufactured in this example was 5.1 μm in the red subpixel where a red color filter was provided, and 5.7 μm in both the green and blue subpixels where green and blue color filters were provided respectively. The difference in cell gap "d" between the subpixels is a result, as in the other examples herein, of the different thicknesses of the color filters. In other words, because the red color filter has a thickness greater than the green and blue color filters, the cell gap "d" in the red subpixel is less than that in the green and blue subpixels. The LC material birefringence was 0.084 at room temperature. The left handed liquid crystal material was Merck's Model No. ZLI4718.

EXAMPLE 6

In this example, an "X-buffed" NW light valve pixel was constructed and tested using white light. A rear linear polarizer was provided having a transmission axis defining a first direction and a front linear polarizer was provided having a transmission axis defining a second direction wherein the first and second directions were substantially perpendicular to one another, thus, defining a normally white light valve. A rear retardation film having an optical axis approximately parallel to the transmission axis of the rear polarizer was provided between the rear polarizer and a rear orientation film. The rear orientation film had a buffing or orientation direction substantially parallel to the direction defined by the transmission axis of the front polarizer. A front retardation film having an optical axis about parallel to the transmission axis of the front polarizer was disposed between the front polarizer and a front orientation film. The front orientation film had an orientation or buffing direction substantially perpendicular to that of the rear orientation film.

In this example, the rear and front retardation films were of the biaxial type. Biaxial retardation films can be characterized by two separate retardation values: $d\cdot\Delta_{ZX}$ and $d\cdot\Delta_{ZY}$. The local X optical axes of the rear and front biaxial retardation films in this light valve were oriented about parallel to their closest adjacent polarizer transmission axis. The local X axis of a biaxial retardation film herein means the axis in the direction having the highest index of refraction (n_X is always the largest index of refraction and n_Z is the lowest). The X, Y, and Z directions (axes) of the biaxial retardation films herein are separate and distinguished from the X, Y, and Z directions (FIG. 6) of the display. In this example, the axis having the retardation value of $d\cdot\Delta_{ZX}$=−168 nm had the highest or largest index of refraction. Both the rear and front biaxial retardation films were obtained from Allied Signal Corporation as Sample No. 4.0. The indices of refraction of the biaxial retardation films of this example were n_X=1.4305; n_Y=1.4275; and n_Z=1.4261. The liquid crystal material had a birefringence of 0.084 at room temperature and was Merck's Model No. ZLI4718. The films therefore had retardation values $d\cdot\Delta_{ZX}$=−168 nm and $d\cdot\Delta_{ZY}$=−53.3 nm.

FIG. 45 is a contrast ratio curve graph illustrating the measured results of the light valve of this example. In FIG. 45, V_{ON} was 6.0 V and V_{OFF} was 0.2 V. As shown, the 10:1 contrast ratio curve extends horizontally off the graph along the 0° vertical viewing axis, thus, defining a horizontal viewing range of greater than about 120°. Furthermore, the 30:1 contrast ratio curve defines a total viewing range along the 0° vertical viewing axis of about 95°–100°. This is a significant improvement over the prior art. The 10:1 contrast ratio curve in the vertical direction along the 0° horizontal viewing axis covers a range of about 75°.

This example illustrates that when a light valve according to this invention is provided with biaxial rear and front retardation films, excellent viewing zone and contrast ratios result and constitute a significant improvement over the prior art.

EXAMPLE 7

FIG. 40 is a computer simulation contrast ratio curve graph illustrating a simulated liquid crystal display according to another embodiment of this invention where the optical axes of the rear and front retardation films are rotated +4° symmetrically. Due to this positive rotation, the center of the viewing zone is shifted to a position substantially

above the 0° vertical viewing axis. As shown, the viewing zone of this display is centered about the +20° vertical viewing axis because of the +4° symmetrical rotation of the retardation films.

With reference to FIG. 11(c), the axis R_F of this embodiment is rotated or oriented clockwise relative to P_F and B_1 defining an angle of 2° therebetween. Also, axes R_R of this embodiment is oriented counterclockwise 2° relative to P_R and B_2. As a result, the angle δ between the optical axes of the retardation films is 94° due to the +4° symmetrical rotation of the retardation film axis. The display of this embodiment would be desirable in situations where a viewing zone centered above the 0° vertical viewing axis was desired. The simulation of FIG. 40 used a V_{ON} of 6.8 V, a green wavelength of 550 nm, and 160 nm retarders. The transmission axes of the polarizers as opposed to the optical axes of the retardation films may instead be rotated to shift the location of the viewing zone in certain other embodiments of this invention. However, rotation of the polarizer axes does not provide as good of results as does the rotation of the retarder axes.

EXAMPLE 8

FIG. 43 is a computer simulation of a liquid crystal display according to yet another embodiment of a NW "X-buffed" LCD of this invention. This embodiment is similar to that illustrated and described in the first embodiment of this invention except that the rear and front retardation films 3 and 7 are negatively birefringent and uniaxial. The optical axes of these retardation films are oriented in the "Z" direction, or in other words, in a direction approximately perpendicular to the planes defined by the retardation films. The display of this embodiment, simulated by FIG. 43, had a cell gap of 5.70 µm, utilized a wavelength of 550 nm in testing the display, a V_{ON} of 6.0 volts, was "X-buffed," and a temperature of about 30° C.

The rear and front retardation films of this embodiment had retardation values of $d\cdot\Delta_{ZX}=d\cdot\Delta_{ZY}=-160$ nm. These films are "uniaxial" because $d\cdot\Delta_{ZX}=d\cdot\Delta_{ZY}$. The retardation value $d\cdot\Delta_{ZX}$ is defined as meaning $d\cdot(n_Z-n_X)$ where "n" is the index of refraction of a particular axis and "d" is the thickness of the retardation film. The retardation films of this embodiment were negative because the parameter n_X was greater than the parameter n_Z. The X, Y, and Z directions of the biaxial retardation films herein are separate and distinguished from the X, Y, and Z directions defining the coordinates of the display.

The term n_X herein always represents the largest index of refraction, and n_Z always represents the smallest. The rear and front polarizers had transmission axes which are substantially perpendicular to one another. The rear retardation film was disposed between the rear polarizer and the rear orientation film, and the front retardation film is between the front polarizer and the front orientation film. The negatively birefringent uniaxial retardation films of this embodiment are obtainable from the University of Akron and are disclosed in U.S. Pat. No. 5,071,997 as soluble polyimides and/or copolyimides.

As can be seen in FIG. 43, this embodiment achieves outstanding contrast ratios at very large viewing angles. For example, the 50:1 contrast ratio curve on the 0° vertical viewing axis defines a range of almost 100° horizontally. This is a significant improvement over the prior art.

EXAMPLE 9

FIG. 44 is a computer simulation contrast ratio graph of another NW embodiment of this invention which utilizes biaxial front and rear retardation films each having retardation values $d\cdot\Delta_{ZX}=-160$ nm and $d\cdot\Delta_{ZY}=-60$ nm. Because the retardation values are negative, the films have negative birefringence. $d\cdot\Delta_{ZX}$ is defined as $d\cdot(n_Z-n_X)$ wherein n_X is the largest index of refraction in the film and n_Z is the smallest. Therefore, $d\cdot\Delta_{ZX}$ is always the largest retardation value herein. The graph of FIG. 44 was plotted using the parameters of V_{ON}=6.0 volts, a LC birefringence of 0.084, a V_{OFF} of 0.9 V, a cell gap of 5.70 µm, a temperature of about 30° C., an "X-buffed" configuration, and a wavelength of 550 nm. The local X' is the axis with the largest index of refaction, or n_X. The local X' optical axis of each retardation film is oriented substantially parallel to the adjacent polarizer transmission axis. In other words, the local X' axis of the rear retardation film is substantially parallel to the transmission axis of the rear polarizer, and the local X' optical axis of the front biaxial retardation film is substantially parallel to the front polarizer transmission axis. The local X' optical axis in this embodiment has the aforesaid retardation value of $d\cdot\Delta_{ZX}=-160$ nm, because n_X was the largest index of refraction. The rear and front polarizer axes define an angle of about 90° therebetween. The axis with the smallest index of refraction, or n_Z, is oriented about perpendicular to the planes defined by the retardation films. As shown in FIG. 44, the embodiment of this invention using the aforesaid biaxial retardation films achieves excellent contrast ratios at large viewing angles. Again, the 50:1 contrast ratio curve along the 0° vertical viewing axis defines a range of about 100° horizontally.

The specific electrodes and substrates present in the displays and light valves of the above described examples are conventional and were not described or shown for purposes of simplicity.

FIG. 41 is a cross-sectional view of the structural arrangement of a typical liquid crystal display pixel envisioned by this invention. For example, the optical arrangement shown and described in FIGS. 11(a)–11(c) may be used in conjunction with the structural arrangement shown in FIG. 41. Normally incident light enters the pixel and first proceeds through rear linear polarizer 1 and is polarized thereby. After proceeding through the polarizer 1, the normally incident light proceeds through the rear retardation film 3 and the rear transparent substrate 19. The transparent substrates 19 and 20 are preferably made of glass, but also may be made of plastic, quartz, or the like. After proceeding through the rear transparent substrate 19, the light then enters the lower pixel electrode 24 and passes therethrough without being substantially optically affected. The light then proceeds through the rear orientation film 21, a liquid crystal layer 5, the front orientation film 22, and the front electrode layer 25. After proceeding through electrode 25, the light then propagates through the front transparent substrate 20, front retardation film 7, and finally comes to the front or exit linear polarizer 9. When the pixel is in the OFF state, the light proceeds through the linear polarizer 9 toward a viewer. However, when the pixel is in the ON or energized state, the exit polarizer 9 absorbs the light of the pixel and the display appears darkened. Also, color filters (not shown) may be provided at any point between the transparent substrates, and preferably between the front substrate 20 and the electrode layer 25 thereby creating a multicolored pixel including a plurality of colored subpixels. It is understood, of course, that retardation films 3 and 7 may also serve as the buffing layers. In such an embodiment films 3 and 7 are replaced and relocated into the location of buffing films 21 and 22 respectively. It is further understood that retarder films 3 and 7 when not replacing buffing films 21 and 22 may

be relocated so as to be between their respective driving electrode (24 and 25) and glass substrate (19 and 20) respectively. By arranging the optical elements of this structural arrangement (FIG. 41) as taught by certain optical embodiments of this invention, the aforesaid improved contrast ratios over predetermined ranges of viewing angles may be achieved.

An alternative structural arrangement envisioned by this invention, is a normally white pixel similar to the one shown in FIG. 41, except that the rear and front retardation films 3 and 7 are disposed between the substrates 19 and 20. The rear retardation film is sandwiched between, for example, the rear substrate 19 and the rear electrode 24, and the front retardation film is disposed between the front substrate 20 and the front electrode 25. All embodiments of this invention may be practiced in such a structural arrangement with excellent contrast ratios over a large range of viewing angles being realized.

Furthermore, the retardation films according to certain embodiment of this invention may be personalized or patterned according to the wavelength or color of each subpixel as taught by our commonly owned copending patent application filed Dec. 2, 1993 entitled "Liquid Crystal Display With Patterned Retardation Films," Ser. No. 08/160,731, the disclosure of which is incorporated hereby by reference. In other words, a retardation film within a red subpixel may have a retardation value different than a retardation film in a green or blue subpixel.

FIG. 42 is a partial cut-away view of a typical active matrix liquid crystal pixel array as envisioned by this invention. Herein, the rear and front retardation films, which are not specifically shown in FIG. 42, are sandwiched between their adjacent polarizers 1 and 9, and their adjacent substrates 19 and 20. The individual pixels 30 shown in FIG. 42 are driven by conventional TFTs 31 which act as switching devices to selectively drive each pixel 30. Conventional transparent ITO electrodes 33 connect the individuals TFTs 31 to their respective pixels 30. Parallel conductive row lines 35 drive either the gate or drain electrodes of the TFTs 31. Column lines 37 drive the other of the gate and drain electrodes of a TFTs thereby selectively driving the individual pixels 30 when a specific TFT has both its gate and drain electrodes energized.

The simulations, light valves, and displays of FIGS. 7–45 herein were twelve o'clock buffed. Therefore, the rear orientation or buffing directions went from the lower right to the upper left, and the front orientation or buffing direction went from the upper right to the lower left.

The pretilt angle of the displays, light valves, and simulations of FIGS. 1–3 and 7–45 herein is about 3°, and the value of "d/p" (thickness/natural pitch of the liquid crystal material) of the liquid crystal layer of these Figures is set to about 0.25.

The computer simulations herein were conducted using simulation software written by Dr. Dwight Berreman, Scotch Plains, N.J. The software is described and referenced in one of Dr. Berreman's publications titled "Numerical Modelling of Twisted Nematic Devices," Phil. Trans. R. Soc. Lond. A309, 203–216 (1983) which was printed in Great Britain.

Once given the above disclosure, many other features, modifications, and improvements will become apparent to the skilled artisan. Such other features, modifications, and improvements are, therefore, considered to be a part of this invention, the scope of which is to be determined by the following claims:

We claim:

1. A normally white twisted nematic liquid crystal display comprising:

a liquid crystal layer for twisting at least one normally incident visible wavelength of light from about 80°–100° as it passes therethrough when said liquid crystal layer is in substantially an off state thereby defining a twisted nematic display;

first and second negative biaxial retarders, each of said first and second negative biaxial retarders defined by $n_x > n_y > n_z$, where n_x, n_y, and n_z are respective indices of refraction for each of said biaxial retarders; and

wherein said first negative biaxial retarder has a retardation value $d \cdot (n_z - n_x)$ of from about −100 to −200 nm.

2. The normally white display of claim 1, wherein the thickness of said liquid crystal layer is from about 4.5 to 6.5 μm, and the birefringence of said liquid crystal is from about 0.075 to 0.095.

3. The normally white display of claim 2, further comprising a front polarizer and a rear polarizer, wherein a transmission axis of the front polarizer is aligned substantially perpendicular to a transmission axis of the rear polarizer.

4. The normally white display of claim 1, wherein said first and second negative biaxial retarders each are made of a polyimide material.

5. The normally white display of claim 1, wherein said liquid crystal layer has a thickness of from about 4.5 to 6.0 μm.

* * * * *

TAB 3

US006226065B1

(12) **United States Patent**
Abileah et al.

(10) **Patent No.: US 6,226,065 B1**
(45) **Date of Patent: *May 1, 2001**

(54) **LIQUID CRYSTAL DISPLAY HAVING HIGH CONTRAST VIEWING ZONE CENTERED IN POSITIVE OR NEGATIVE VERTICAL REGION**

(75) Inventors: **Adiel Abileah**, Farmington Hills; **Gang Xu**, Royal Oak, both of MI (US)

(73) Assignee: **OIS Optical Imaging Systems, Inc.**, Troy, MI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/334,267**

(22) Filed: **Jun. 16, 1999**

Related U.S. Application Data

(63) Continuation of application No. 09/048,322, filed on Mar. 26, 1998, which is a continuation of application No. 08/747,671, filed on Nov. 12, 1996, now Pat. No. 5,737,048, which is a continuation of application No. 08/255,971, filed on Jun. 8, 1994, now Pat. No. 5,576,861, which is a continuation-in-part of application No. 08/235,691, filed on Apr. 29, 1994, now Pat. No. 5,594,568, and a continuation-in-part of application No. 08/167,652, filed on Dec. 15, 1993, now Pat. No. 5,570,214.

(51) **Int. Cl.**^{7} **G02F 1/1335**

(52) **U.S. Cl.** **349/120**; 349/119

(58) **Field of Search** 349/117, 121, 349/118, 119, 120

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,900,248	8/1975	Nagasaki	349/117
4,385,806	5/1983	Fergason	349/119
4,436,379	3/1984	Funada et al.	349/75

(List continued on next page.)

FOREIGN PATENT DOCUMENTS

0349900	1/1990	(EP) .
0367616	5/1990	(EP) .
0576931	1/1994	(EP) .
0679921	11/1995	(EP) .
0774682	5/1997	(EP) .
55-45037	3/1980	(JP) .
63-239421	10/1988	(JP) .
313916	1/1991	(JP) .
369915	3/1991	(JP) .

OTHER PUBLICATIONS

CPA of U.S. Serial No. 09/048,322.
"Wide Viewing Angle LCD Using Retardation Films" by Yamagishi, Watanabe and Yokoyama.
"Phase Difference Plate and Liquid Crystal Electro–Optical Device Using This Plate" by Okumura.

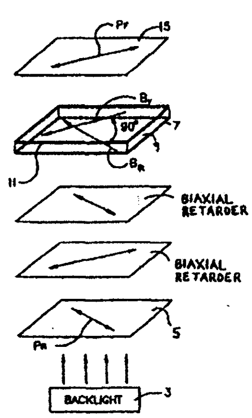
(List continued on next page.)

Primary Examiner—William L. Sikes
Assistant Examiner—Dung Nguyen
(74) *Attorney, Agent, or Firm*—Laff, Whitesel & Saret, Ltd.

(57) **ABSTRACT**

A normally white liquid crystal display is provided with a positively birefringent uniaxial retardation film having a retardation value of from about 100–200 nm. The retardation film is provided on one side of the liquid crystal layer, the liquid crystal being sandwiched between a pair of orientation or buffing films which orient the liquid crystal molecules adjacent thereto in predetermined directions. The optical axis of the retardation film is rotated from about 2°–20°, most preferably from about 6°–10° relative to the buffing direction on the opposite side of the liquid crystal layer. This rotation of the retardation film optical axis allows for the high contrast ratio viewing zone of the display to be shifted vertically into either the positive or negative vertical viewing region depending upon the direction of rotation of the retardation film optical axis. Alternatively, biaxial retardation films having similar retardation values may be utilized according to the teachings of this invention.

4 Claims, 16 Drawing Sheets



U.S. PATENT DOCUMENTS

4,632,514	12/1986	Ogawa et al.	349/160
4,652,088	3/1987	Kando et al.	349/103
4,674,841	6/1987	Buzak	349/117
4,686,519	8/1987	Yoshida et al.	349/95
4,693,562	9/1987	Hasegawa et al.	849/103
4,701,028	10/1987	Clerc et al.	349/117
4,844,569	7/1989	Wada et al.	349/117
4,852,976	8/1989	Suzuki	349/119
4,889,412	12/1989	Clerc et al.	349/118
4,957,349	9/1990	Clerc et al.	349/117
4,973,137	11/1990	Kodaki	349/119
4,984,873	1/1991	Takiguchi et al.	349/121
4,984,874	1/1991	Yamamoto et al.	349/119
4,991,941	2/1991	Kalmanash	349/117
4,995,704	2/1991	Yamamoto et al.	349/119
5,018,839	5/1991	Yamamoto et al.	349/121
5,032,008	7/1991	Yamamoto et al.	349/119
5,071,997	12/1991	Harris	528/353
5,107,356	4/1992	Castleberry	349/119
5,124,824	6/1992	Kozaki et al.	349/120
5,132,826	7/1992	Johnson et al.	349/117
5,138,474	8/1992	Arakawa	349/120
5,150,235	9/1992	Haim et al.	349/117
5,150,237	9/1992	Iimura et al.	349/118
5,157,529	10/1992	Koopman et al.	349/117
5,179,457	1/1993	Hirataka et al.	349/119
5,184,236	2/1993	Miyashita et al.	349/119
5,189,538	2/1993	Arakawa	349/120
5,194,975	3/1993	Akatsuka et al.	349/118
5,196,953	3/1993	Yeh et al.	349/119
5,227,903	7/1993	Miyazawa et al.	349/119
5,229,039	7/1993	Ikeda et al.	349/106
5,231,521	7/1993	Johnson et al.	349/117
5,237,438	8/1993	Miyashita et al.	349/119
5,241,408	8/1993	Ishikawa et al.	349/117
5,250,214	10/1993	Kanemoto et al.	349/117
5,344,916	9/1994	Harris et al.	528/353
5,369,513	11/1994	Akatsuka et al.	349/118
5,448,386	9/1995	Watanabe et al. .	
5,548,426	8/1996	Miyashita et al. .	
5,570,214	10/1996	Abileah et al.	349/117
5,594,568	1/1997	Abileah et al.	349/117

OTHER PUBLICATIONS

"Liquid Crystal Display Device" by Watanabe.

"The Symmetry Property of a 90 Degree Twisted Nematic Liquid Crystal Cell" by Lien.

Patent Abstracts of Japan, 07253573, Mar. 10, 1995.

WO96/15473, Pub. Date May 23, 1996, PCT.

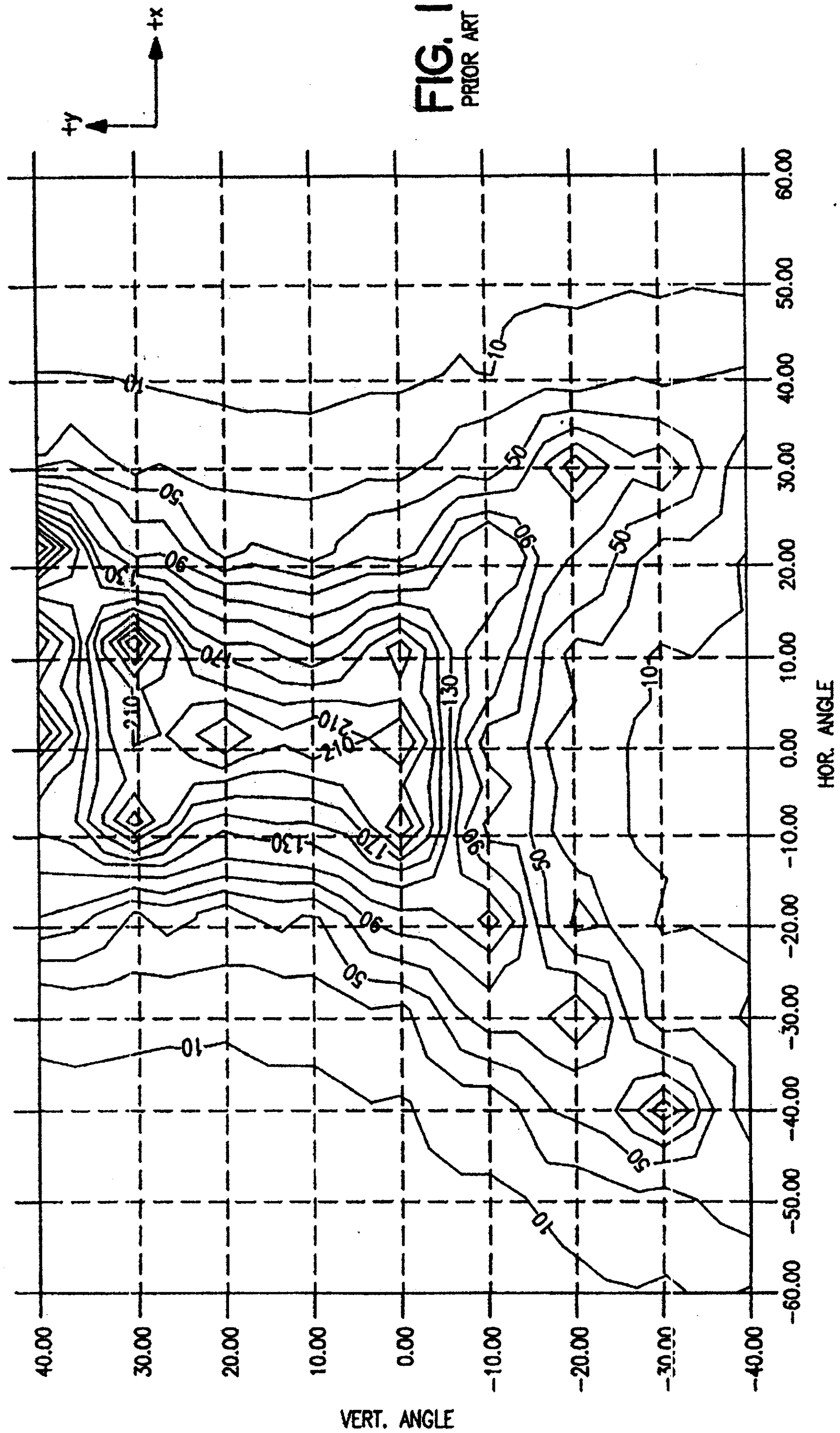


FIG. 1
PRIOR ART

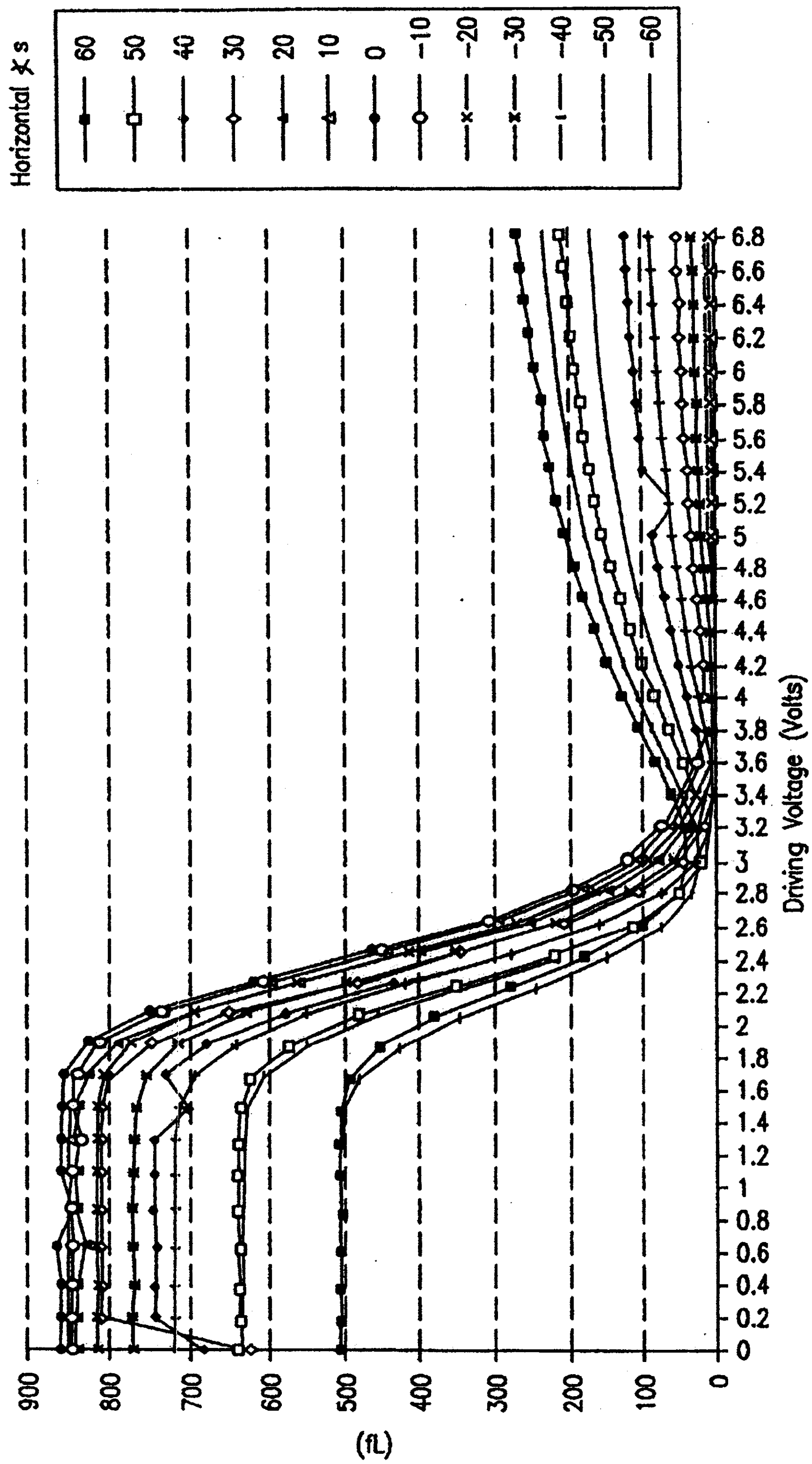


FIG. 2
PRIOR ART

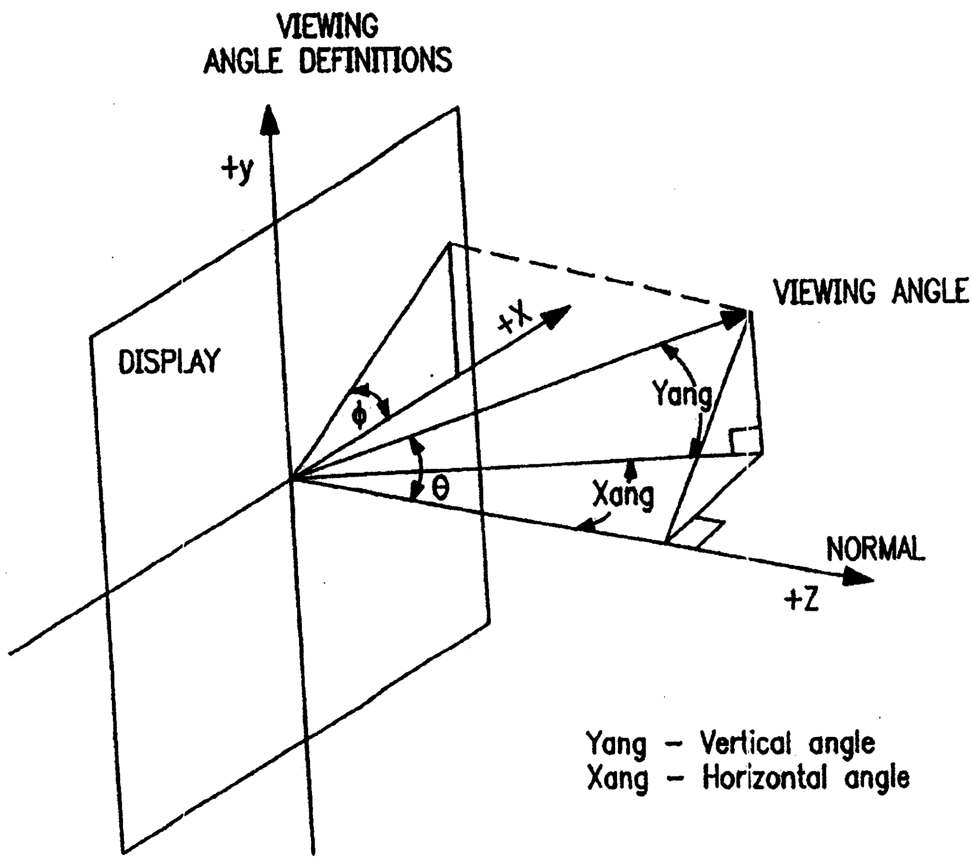

VIEWING
ANGLE DEFINITIONS
+y
DISPLAY
+X
VIEWING ANGLE
Yang
ϕ
θ
Xang
NORMAL
+Z
Yang - Vertical angle
Xang - Horizontal angle

FIG. 3

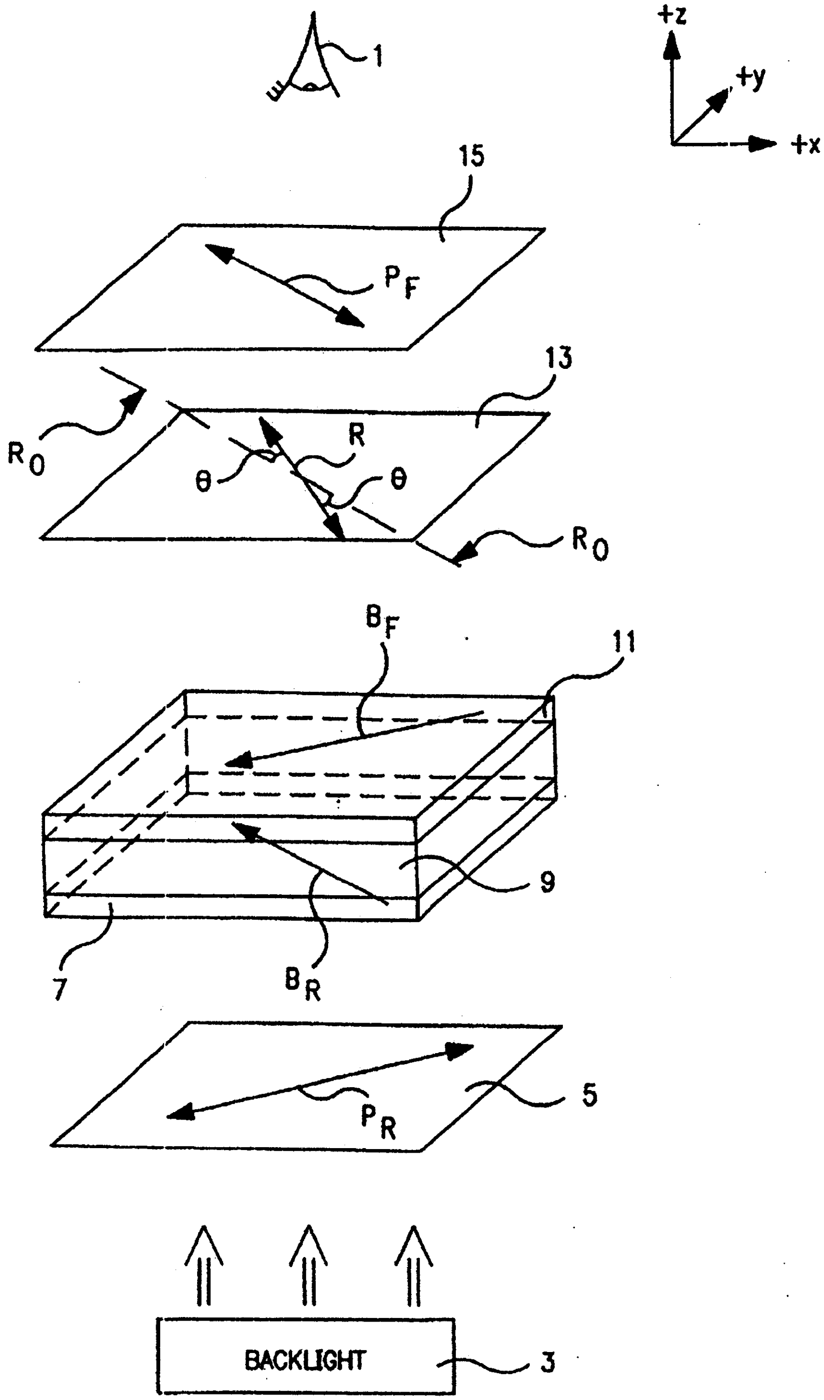


FIG. 4

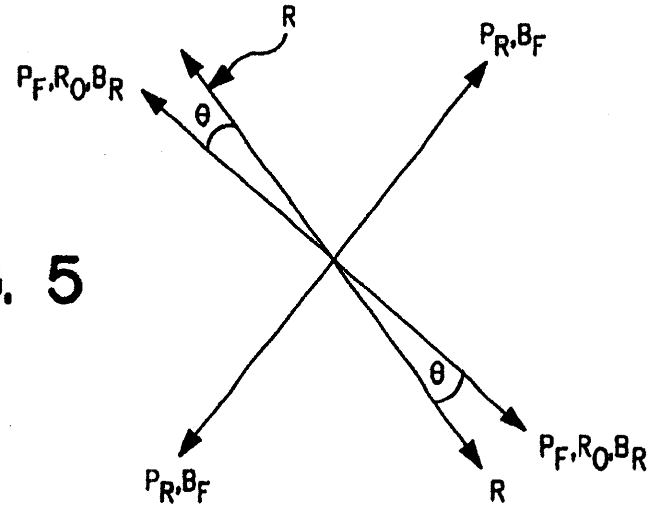

R
P_R, B_F
P_F, R_O, B_R
θ
θ
P_F, R_O, B_R
P_R, B_F
R

FIG. 5

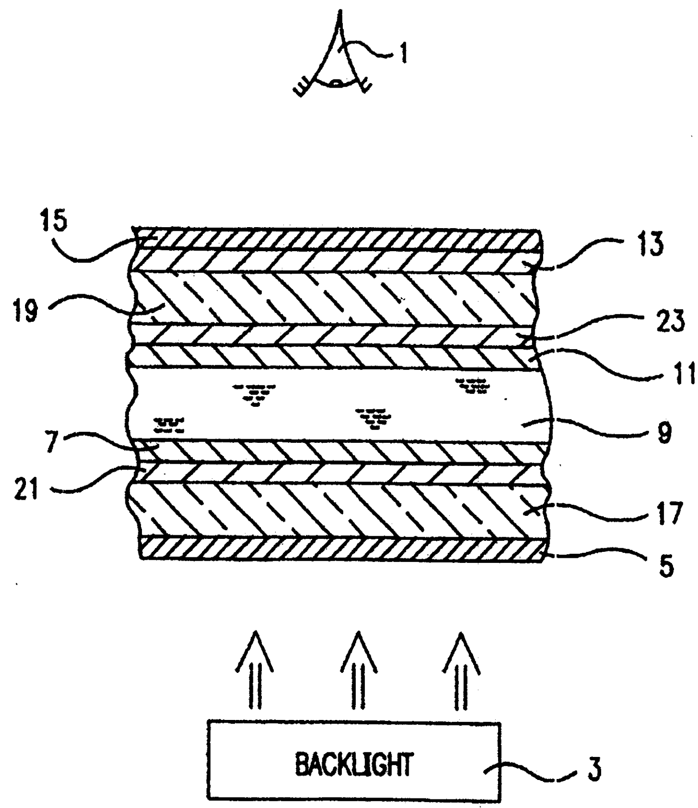

1
15
13
19
23
11
9
7
21
17
5
BACKLIGHT
3

FIG. 6

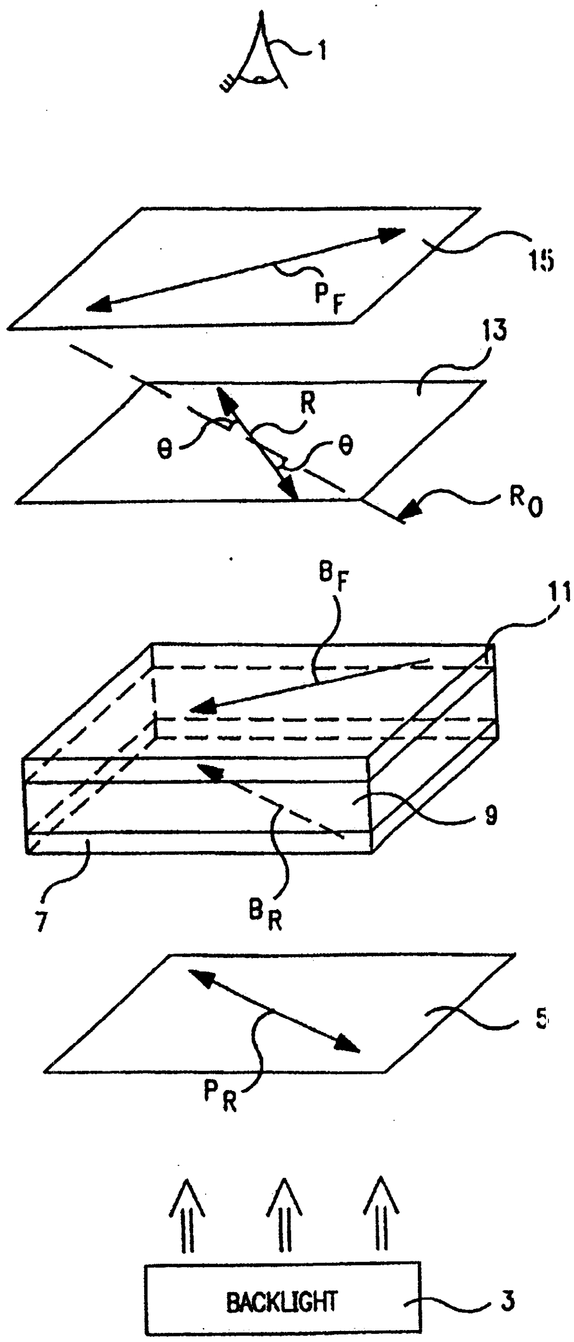


FIG. 7

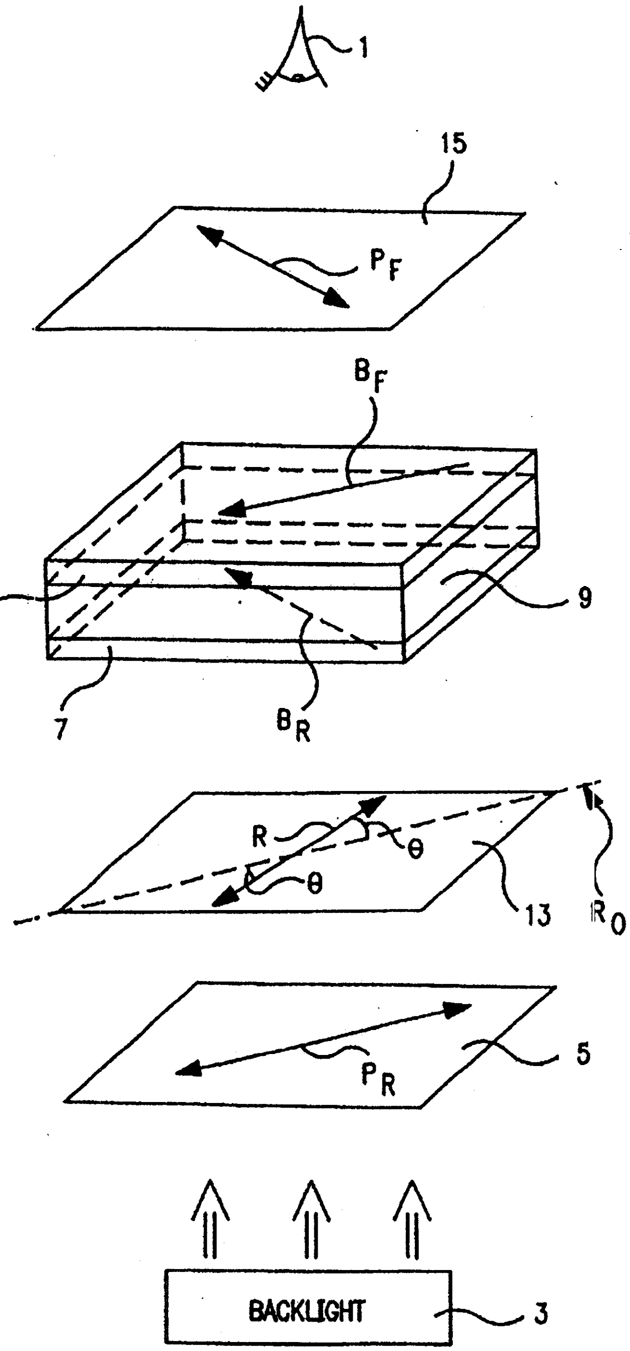
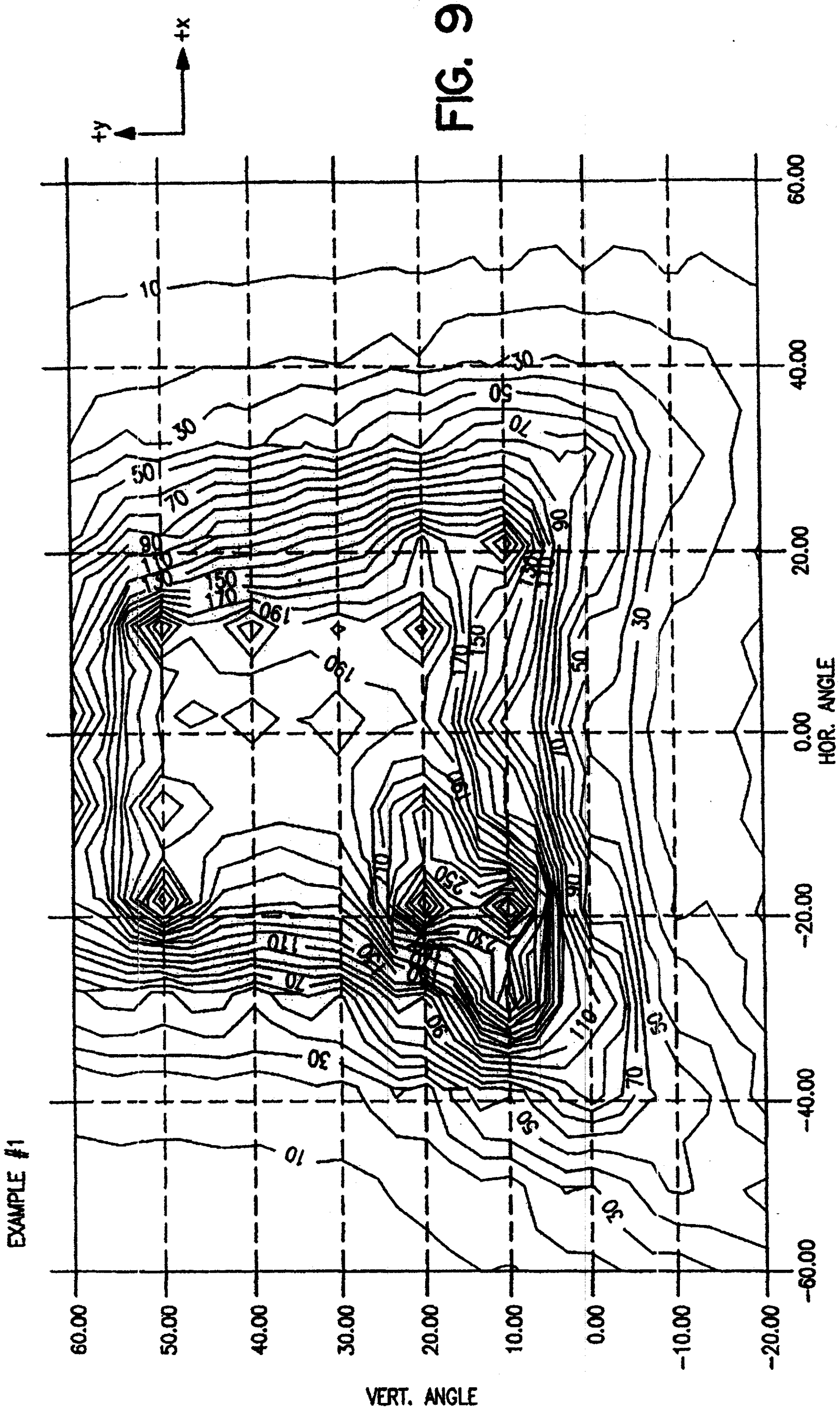


FIG. 8

FIG. 9


+x
+y
EXAMPLE #1
HOR. ANGLE
VERT. ANGLE
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
50.00
30.00
10.00
-10.00

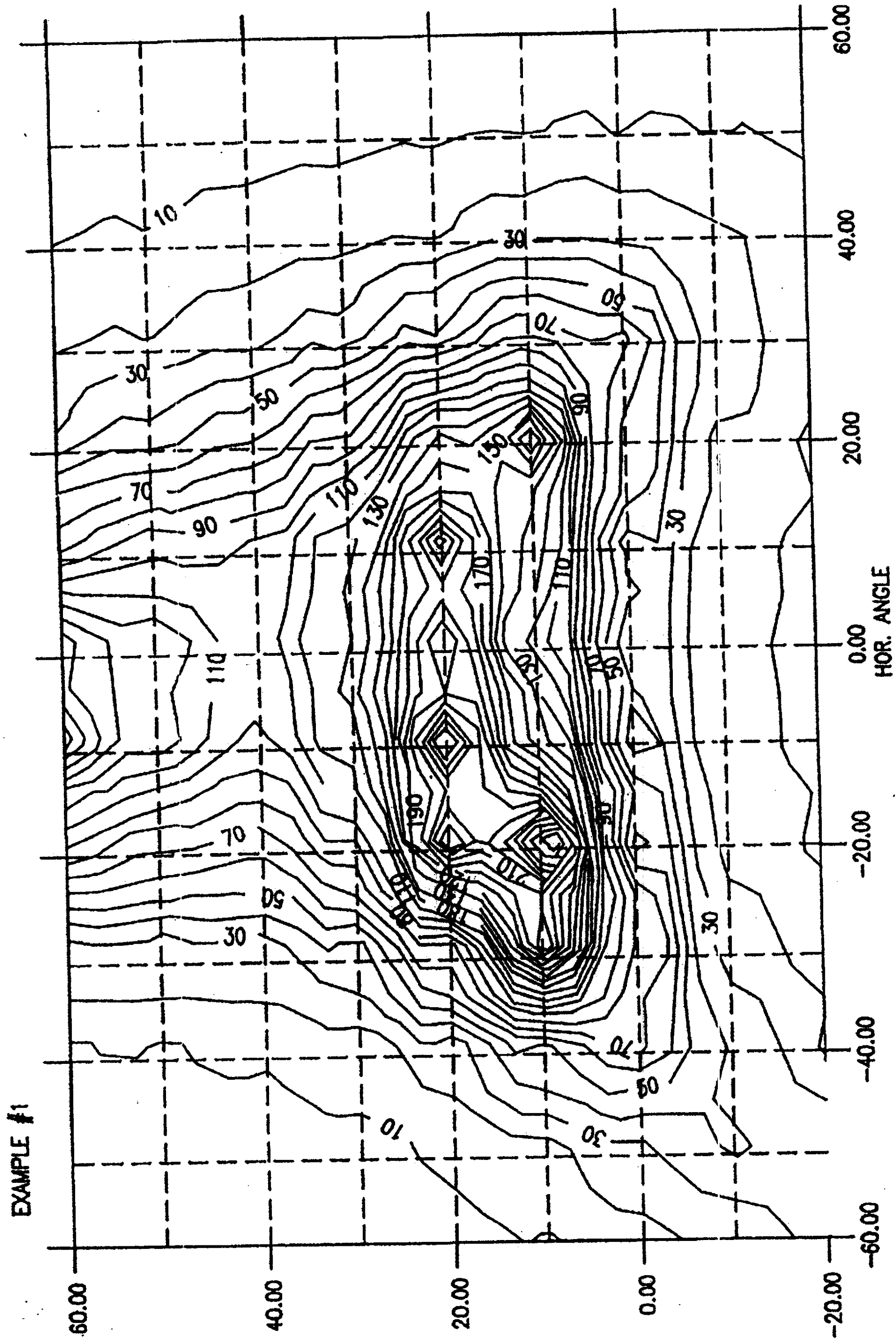


FIG. 10

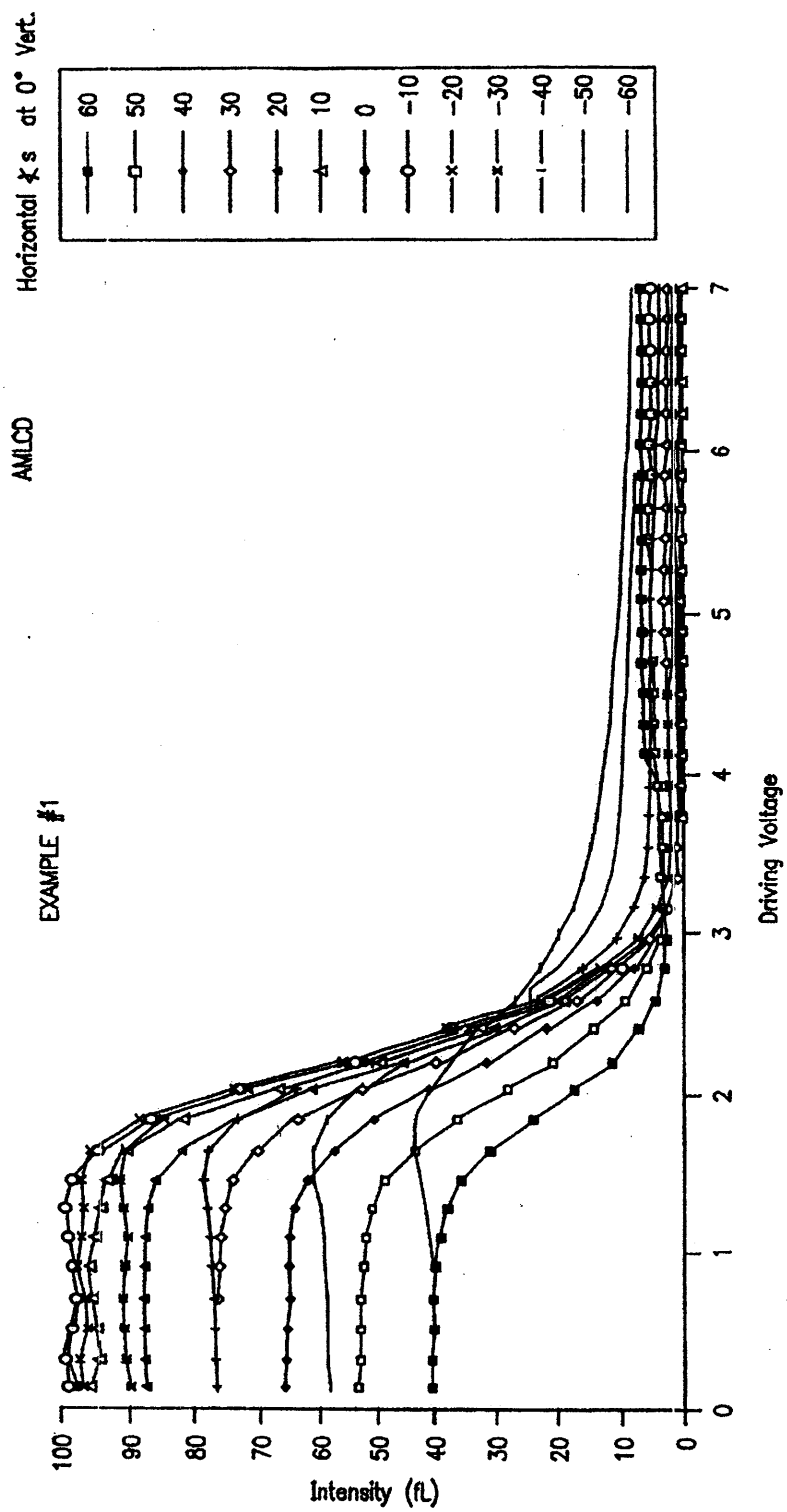

EXAMPLE #1
AMLCD
Horizontal ∢'s at 0° Vert.
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Intensity (fL)
100
90
80
70
60
50
40
30
20
10
0
Driving Voltage
0
1
2
3
4
5
6
7

FIG. 11

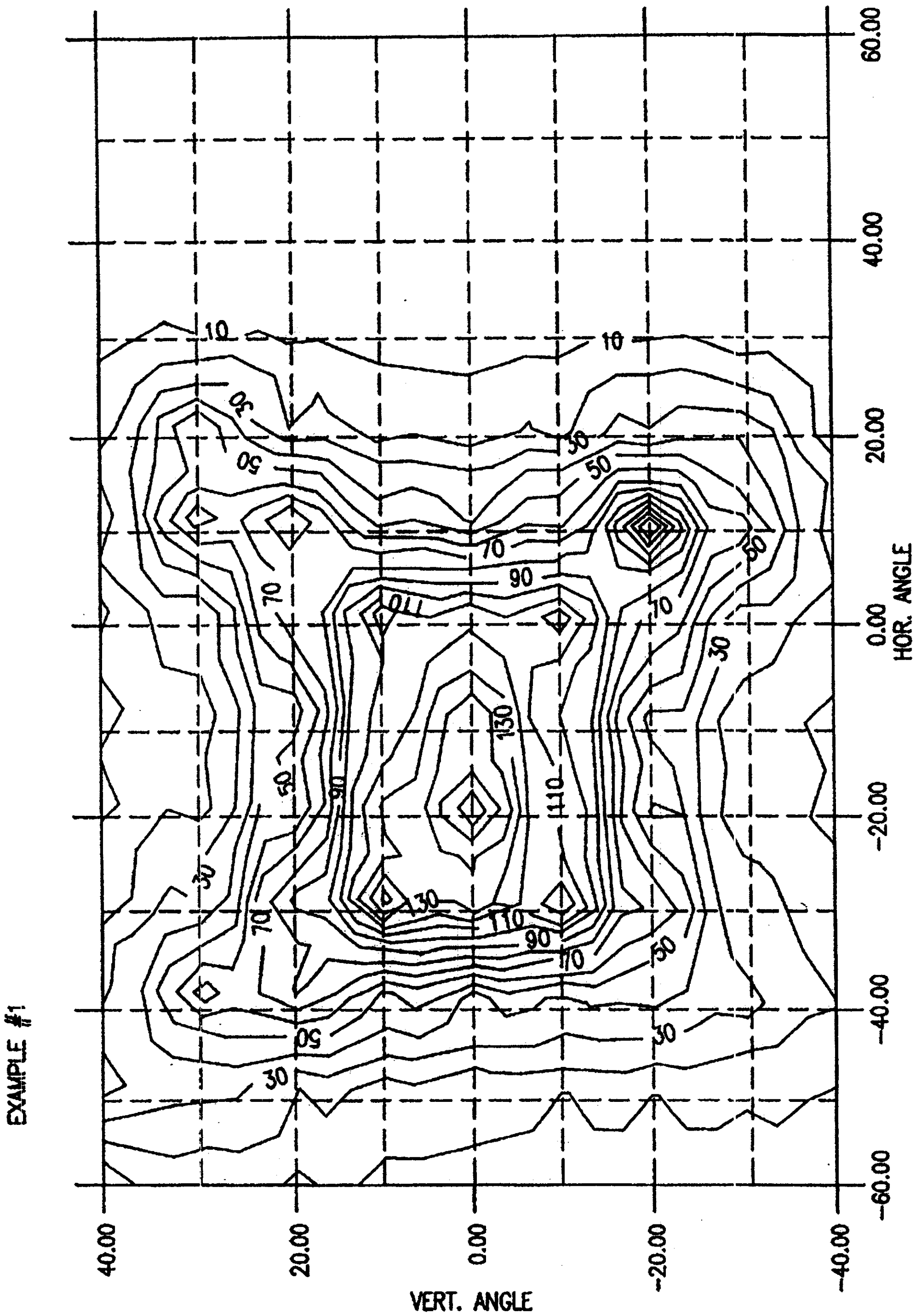

EXAMPLE #1
VERT. ANGLE
40.00
20.00
0.00
-20.00
-40.00
HOR. ANGLE
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
10
30
50
70
90
110
130

FIG. 12a

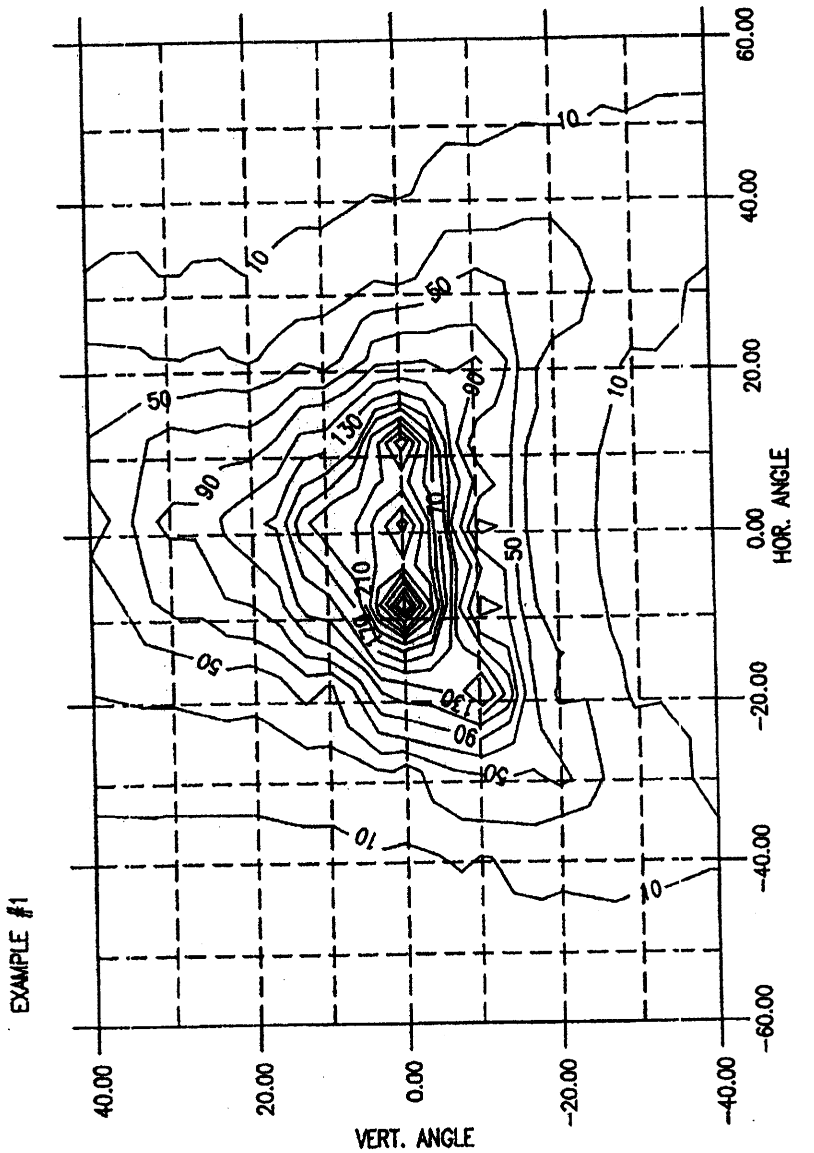
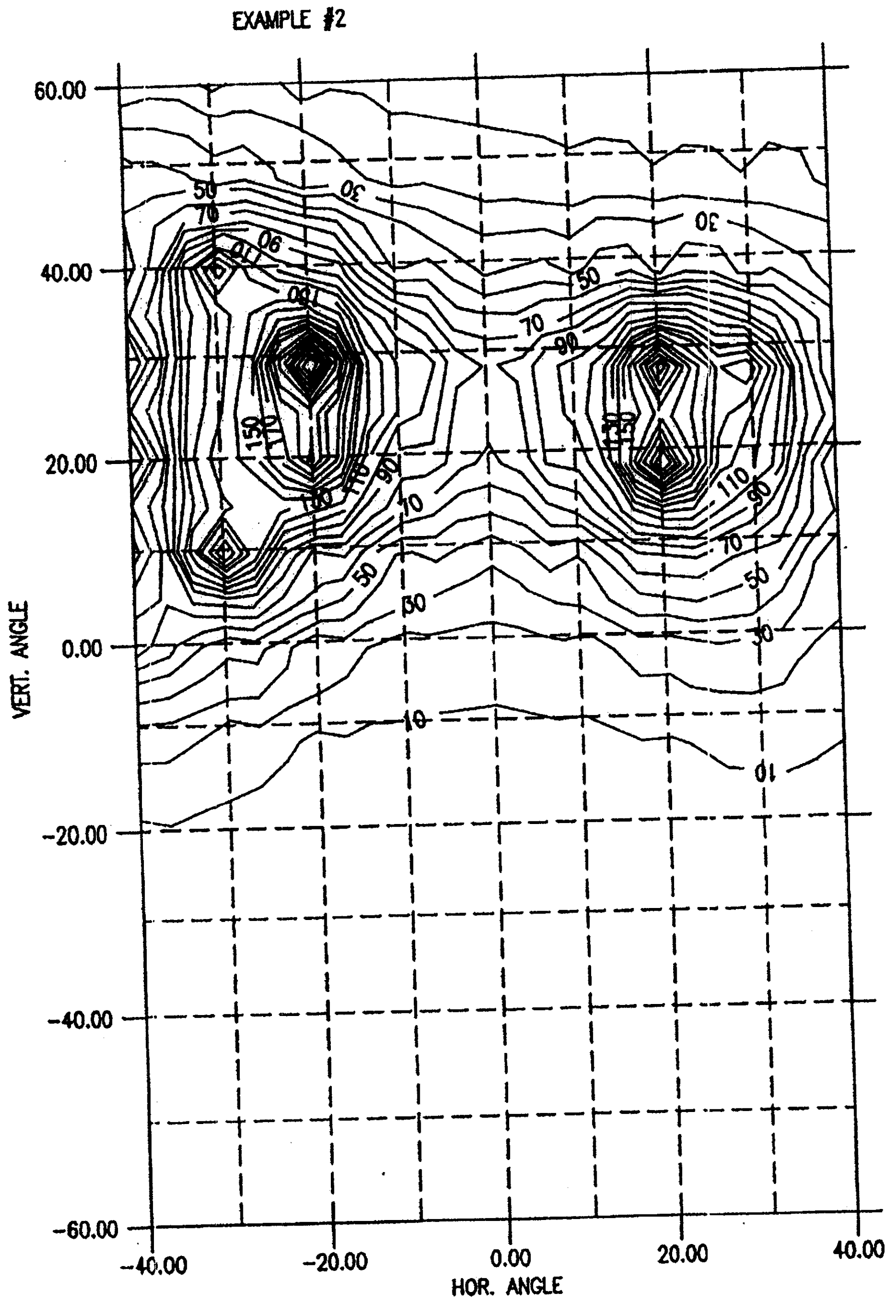
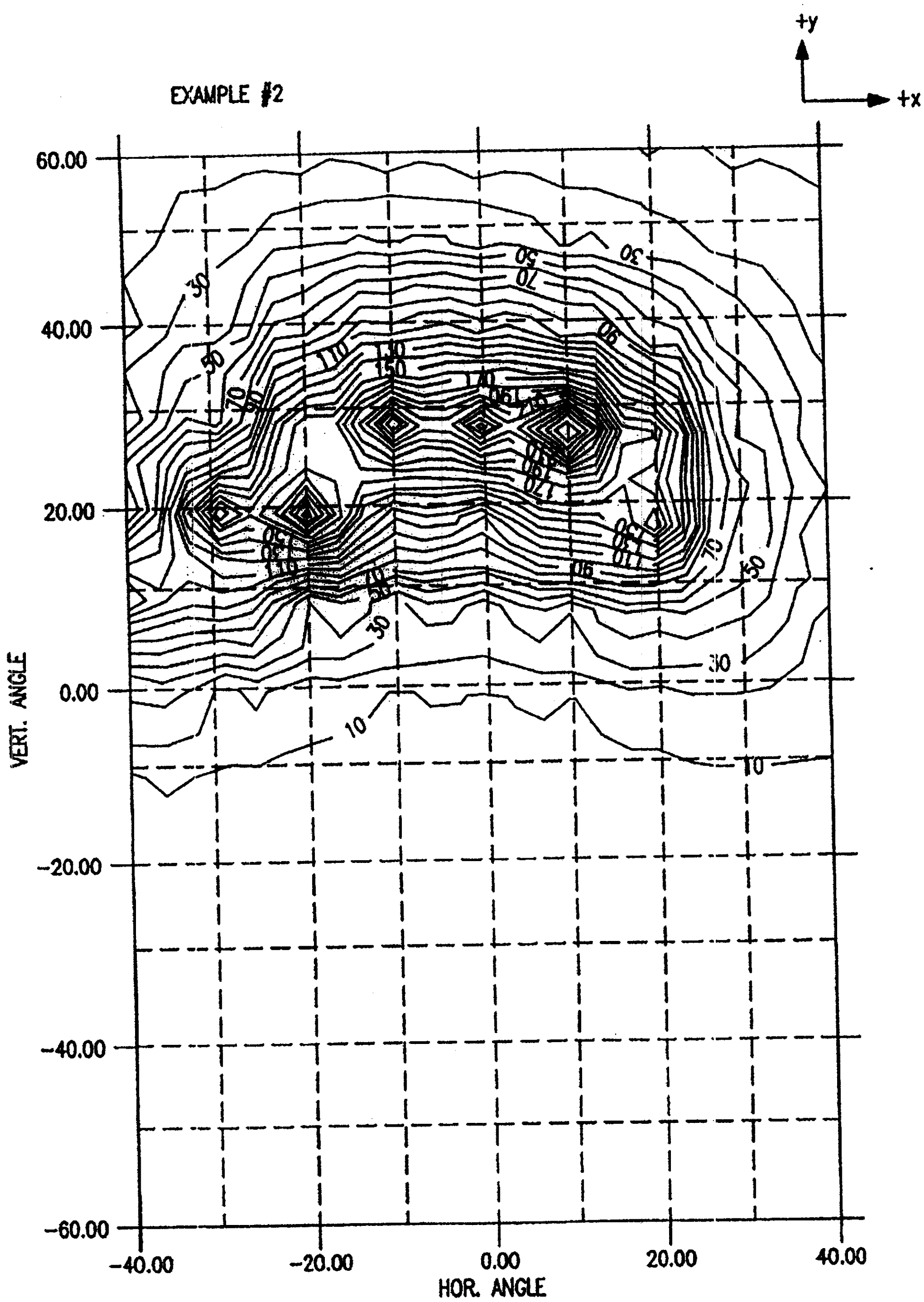

EXAMPLE #1
VERT. ANGLE
HOR. ANGLE
40.00
20.00
0.00
-20.00
-40.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
10
50
90
130
170
210

FIG. 12b



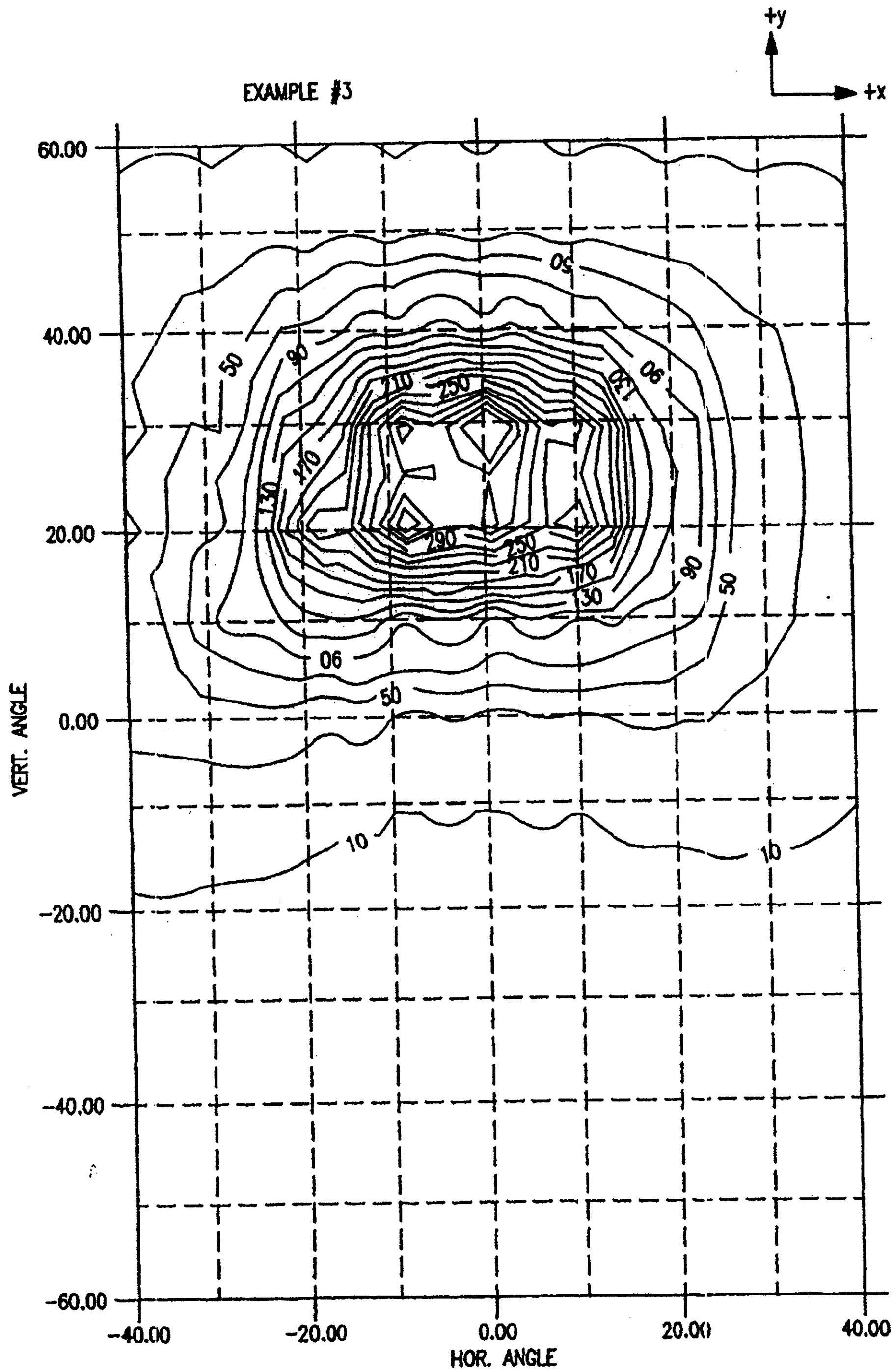
EXAMPLE #2
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
VERT. ANGLE
-40.00
-20.00
0.00
20.00
40.00
HOR. ANGLE
30
50
70
90
110
130
150
10

FIG. 13



EXAMPLE #2
+y
+x
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
VERT. ANGLE
-40.00
-20.00
0.00
20.00
40.00
HOR. ANGLE
30
50
70
90
110
130
150
140
10

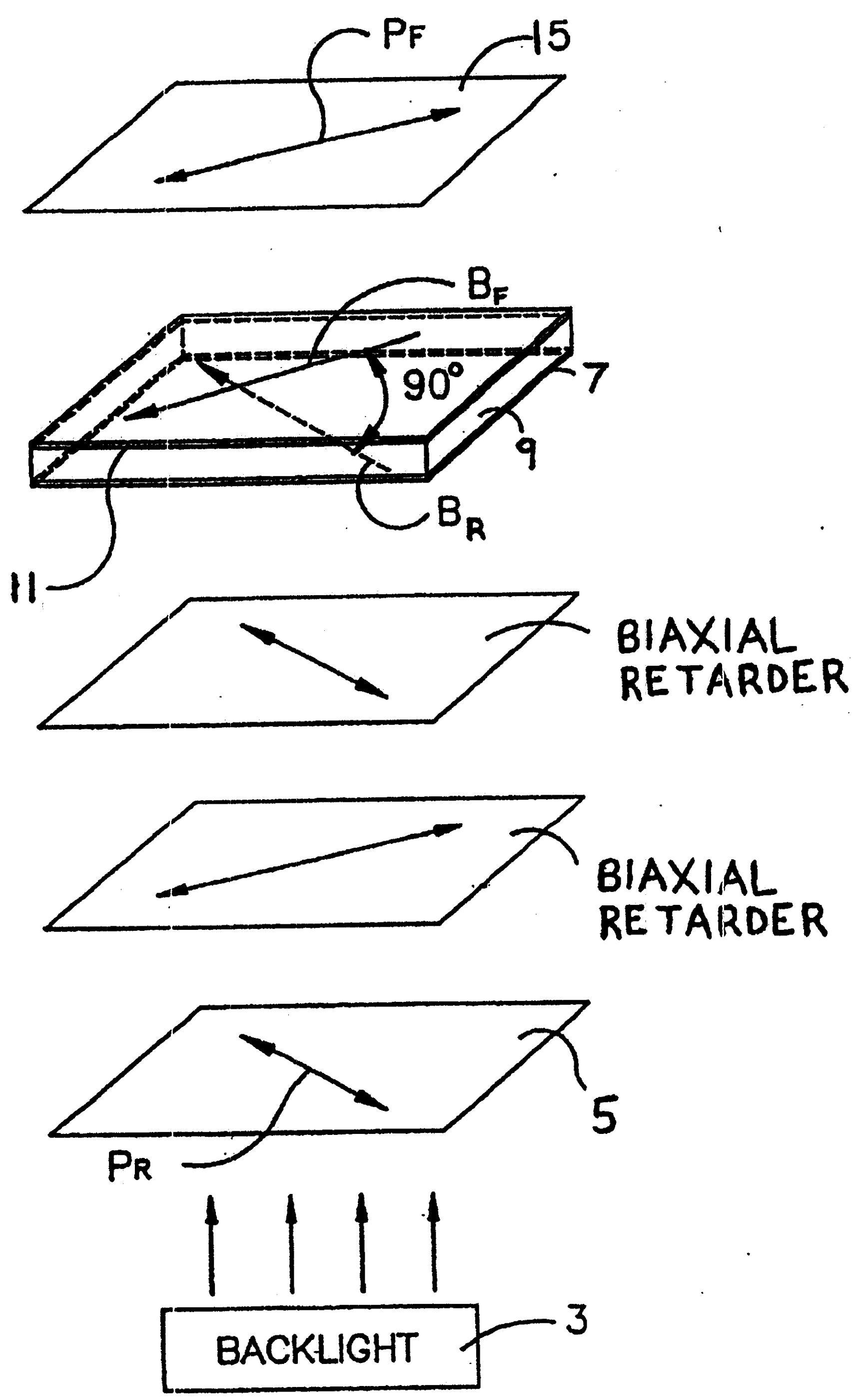
FIG. 14



+y
+x
EXAMPLE #3
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
VERT. ANGLE
-40.00
-20.00
0.00
20.00
40.00
HOR. ANGLE
50
90
130
170
210
250
290
10

FIG. 15

Fig. 16


PF
15
BF
90°
7
9
BR
11
BIAXIAL RETARDER
BIAXIAL RETARDER
5
PR
BACKLIGHT
3

LIQUID CRYSTAL DISPLAY HAVING HIGH CONTRAST VIEWING ZONE CENTERED IN POSITIVE OR NEGATIVE VERTICAL REGION

This is a continuation of application Ser. No. 09/048,322, filed Mar. 26, 1998; which is a cont. of Ser. No. 08/747,671, filed Nov. 12, 1996 (U.S. Pat. No. 5,737,048); which is a cont. of Ser. No. 08/255,971, filed Jun. 8, 1994 (U.S. Pat. No. 5,576,861); which is a CIP of Ser. No. 08/235,691, filed Apr. 29, 1994 U.S. Pat. No. 5,594,568); and a CIP of Ser. No. 08/167,652, filed Dec. 15, 1993 (U.S. Pat. No. 5,570, 214), all of which are incorporated herein by reference.

This invention relates to a liquid crystal display having at least one retardation film. More particularly, this invention relates to a normally white liquid crystal display including a retardation film disposed on one side of the liquid crystal layer, the optical axis of the retardation film being oriented according to the manufacturer's desired specification.

RELATED APPLICATIONS

This is a continuation-in-part of U.S. Ser. No. 08/167,652 (U.S. Pat. No. 5,570,214) filed Dec. 15, 1993, and Ser. No. 08/235,691 (U.S. Pat. No. 5,594,568) filed Apr. 29, 1994, the disclosures of which are hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

Liquid crystal materials are useful for electronic displays because light traveling through a layer of liquid crystal (LC) material is affected by the anisotropic or birefringent value (Δn) of the LC material which in turn can be controlled by the application of a voltage across the LC. Liquid crystal displays (LCDs) are commonly used in applications such as avionic cockpit displays, portable computers, calculators, etc.

Informational data in typical liquid crystal displays is presented in the form of a matrix array of rows and columns of numerals or characters which are generated by a number of segmented electrodes arranged in a matrix pattern. The segments are connected by individual leads to driving electronics which apply a voltage to the appropriate combination of segments and adjacent LC material in order to display the desired data and/or information by controlling the light transmitted through the liquid crystal material.

Contrast ratio is one of the most important attributes considered in determining the quality of both normally white (NW) and normally black (NB) liquid crystal displays. The contrast ratio in a normally white display is determined in low ambient conditions by dividing the "off-state" light transmission (high intensity white light) by the "on-state" or darkened transmitted intensity. For example, if the "off-state" transmission is 200 fL at a particular viewing angle and the "on-state" transmission is 5 fL at the same viewing angle, then the display's contrast ratio at that particular viewing angle is 40 or 40:1 for the particular "on-state" driving voltage utilized.

Accordingly, in normally white LCDs the primary factor adversely limiting the contrast ratio is the amount of light which leaks through the display in the darkened or "on-state". In a similar manner, in normally black displays, the primary factor limiting the contrast ratio achievable is the amount of light which leaks through the display in the darkened or "off-state". The higher and more uniform the contrast ratio of a particular display over a wide range of viewing angles, the better the LCD.

Normally black (NB) twisted nematic displays typically have better contrast ratio contour curves or characteristics then do their counterpart NW displays in that the NB image can be seen better at large viewing angles. However, NB displays are much harder to manufacture than NW displays due to their high dependence on the cell gap or thickness "d" of the liquid crystal layer as well as on the temperature of the liquid crystal material itself. Accordingly, a long-felt need in the art has been the ability to construct a normally white display with high contrast ratios over a large range of viewing angles, rather than having to resort to the more difficult to manufacture NB display to achieve these characteristics.

What is generally needed in NW displays is an optical compensating or retarding element(s), i.e. retardation film, which introduces a phase delay that restores the original polarization state of the light, thus allowing the light to be substantially blocked by the output polarizer in the "on-state". Optical compensating elements or retarders are known in the art and are disclosed, for example, in U.S. Pat. Nos. 5,184,236, 5,196,953, 5,138,474, and 5,071,997, the disclosures of which are hereby incorporated herein by reference.

FIG. 1 is a contrast ratio curve graph for a prior art normally white twisted nematic light valve including a rear linear polarizer having a transmission axis oriented in a first direction, a front or light exit linear polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another, a liquid crystal material having a cell gap "d" of about 5.86 μm and a birefringence (Δn) of about 0.084 at room temperature, a rear bufing or orientation film buffed in the second direction, and a front orientation film buffed in the first direction. The temperature at which FIG. 1 was developed was about 34.4° C. This light valve did not include a retarder.

The contrast ratio curves of FIG. 1 were plotted utilizing a 6.8 volt "on-state" driving voltage, a 0.2 volt "off-state" or V_{OFF} voltage, and by conventionally backlighting the display with white light. As can be seen in FIG. 1, the viewing zone or envelope of the light valve while being fairly broad horizontally in the lower vertical region becomes narrowed or constricted in the positive vertical viewing region. For example, at positive 20° vertical, the 10:1 and greater contrast ratio region extends horizontally over only a total of about 70° while at −20° vertical, this same 10:1 contrast ratio zone extends over a horizontal total of about 100°. Therefore, because of the non-uniform or skewed shape of the viewing zone or envelope shown in FIG. 1, it is evident that viewers in the positive vertical viewing region will have difficulty viewing displayed images at medium and large horizontal viewing angles such as about ±40°. This graph is illustrative of the common problems associated with typical normally white liquid crystal displays in that their contrast ratios are limited at increased horizontal and vertical viewing angles.

FIG. 2 is a driving voltage versus intensity (fL) plot of the prior art light valve described above with respect to FIG. 1, this plot illustrating the gray level behavior of this light valve. The various curves represent horizontal viewing angles from about −60° to +60° along the 0° vertical viewing axis.

Gray level performance and the corresponding amount of inversion are important in determining the quality of an LCD. Conventional liquid crystal displays typically utilize anywhere from about 8 to 64 different driving voltages.

These different driving voltages are generally referred to as "gray level" voltages. The intensity of light transmitted through the pixel(s) or display depends upon the driving voltage utilized. Accordingly, conventional gray level voltages are used to generate dissimilar shades of color so as to create different colors when, for example, the shades are mixed with one another.

Preferably, the higher the driving voltage in a normally white display, the lower the intensity (fL) of light transmitted therethrough. Likewise then, the lower the driving voltage, the higher the intensity of light reaching the viewer. The opposite is true in normally black displays. Thus, by utilizing multiple gray level driving voltages, one can manipulate either a NW or NB liquid crystal display to emit desired intensities and shades of light/color. A gray level V_{ON} is generally known as any driving voltage greater than V_{th} (threshold voltage) up to about 5–6.5 volts.

Gray level intensity in LCDs is dependent upon the display's driving voltage. It is desireable in NW displays to have an intensity versus driving voltage curve wherein the intensity of light emitted from the display or pixel continually and monotonically decreases as the driving voltage increases. In other words, it is desireable to have gray level performance in an NW pixel such that the intensity (fL) at 6.0 volts is less than that at 5.0 volts, which is in turn less than that at 4.0 volts, which is less than that at 3.0 volts, which is in turn less than that at 2.0 volts, etc. Such desired gray level curves across wide ranges of view allow the intensity of light reaching viewers at different viewing angles via the pixel(s) or display to be easily and consistently controlled.

Turning again to FIG. 2, the intensity versus driving voltage curves illustrated therein of the FIG. 1 light valve having no retardation film are undesireable because of the inversion humps present in the areas of the curves having driving voltages greater than about 3 or 3.2 volts. The intensity aspect of the curves monotonically decreases as the driving voltage increases in the range of from about 1.6–3.0 volts, but at a driving voltage of about 3.2 volts, the intensities at a plurality of viewing angles begin to rise as the voltage increases from about 3.2 volts up to about 6.8 volts. Such rises in intensity as the driving voltage increases are known as "inversion humps". Inversion humps lead to the display or light valve emitting different colors via the same pixel at different viewing angles for the same driving voltage. Clearly, this is undesirable. While the inversion humps of FIG. 2 include only rise portions, inversion humps often include both rise and fall portions as will be appreciated by those of ordinary skill in the art, thus enabling the "inversion humps" to actually look like humps.

A theoretically perfect driving voltage versus intensity (fL) curve for an NW display would have a decreased intensity (fL) for each increase in gray level driving voltage at all viewing angles. In contrast to this, the inversion humps of FIG. 2 represent large increases in intensity of radiation emitted from the light valve for each corresponding increase in gray level driving voltage above about 3.2 volts. Accordingly, it would satisfy a long-felt need in the art if a normally white liquid crystal display could be provided with no or little inversion.

U.S. Pat. No. 5,184,236 discloses an NW display including a pair of retardation films provided on one side of the LC layer, these retardation films having retardation values of about 300 nm or greater. The viewing characteristics of the LCDs of this patent could be improved upon with respect to contrast ratio, inversion, and uniformity as well as the position of the viewing zone by utilizing retarders of different values and orientations. Furthermore, it is felt that such improvements may be achieved with a reduced number of retardation films thus reducing the cost and complexity of the display.

The parents of this application, i.e. Ser. Nos. 08/167,652 and 08/235,691 incorporated herein by reference, provide for NW displays with a pair of retardation films having retardation values of about 80–200 nm. While the different embodiments of Ser. Nos. 08/167,652 and 08/235,691 provide excellent results with respect to viewing characteristics, the disclosure of this application allows improved viewing characteristics in the vertical viewing regions while sacrificing certain viewing characteristics at other viewing angles.

FIG. 3 illustrates the angular relationships between the horizontal and vertical viewing axes and angles described herein relative to a liquid crystal display and conventional LCD angles ø and Θ. The +X, +Y, and +Z axes shown in FIG. 3 are also defined in other figures herein. Furthermore, the "horizontal viewing angles" (or X_{ANG}) and "vertical viewing angles" (or Y_{ANG}) illustrated and described herein may be transformed to conventional LCD angles: azimuthal angle ø; and polar angle Θ, by the following equations:

$$\mathrm{Tan}\,(X_{ANG}) = \mathrm{Cosine}\,(\phi)\cdot\mathrm{Tan}\,(\Theta)$$

$$\mathrm{Sine}\,(Y_{ANG}) = \mathrm{Sine}\,(\Theta)\cdot\mathrm{Sine}\,(\phi)$$

or

$$\mathrm{Cosine}\,(\Theta) = \mathrm{Cosine}\,(Y_{ANG})\cdot\mathrm{Cosine}\,(X_{ANG})$$

$$\mathrm{Tan}\,(\phi) = \mathrm{Tan}\,(Y_{ANG}) \div \mathrm{Sine}\,(X_{ANG})$$

The term "rear" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones, and orientation films means that the described element is on the backlight side of the liquid crystal material, or in other words, on the side of the LC material opposite the viewer.

The term "front" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones and orientation films means that the described element is located on the viewer side of the liquid crystal material.

The LCDs and light valves herein include a liquid crystal material with a birefringence (Δn) of 0.084 at room temperature, Model No. ZLI-4718 obtained from Merck.

The term "retardation value" as used herein means "d.Δn" of the retardation film or plate, wherein "d" is the film thickness and "Δn" is the film birefringence.

The term "interior" when used herein to describe a surface or side of elements (or an element itself), means the side or surface closest to the liquid crystal material.

The term "light valve" as used herein means a liquid crystal display including a rear linear polarizer, a rear transparent substrate, a rear continuous pixel electrode, a rear orientation film, an LC layer, a front orientation film, a front continuous pixel electrode, a front substrate, and a front polarizer (without the presence of color filters and driving active matrix circuitry such as TFTs). Such a light valve may also include a retardation film(s) disposed on either side of the LC layer as described with respect to each example and embodiment herein. In other words, a "light valve" may be referred to as one giant pixel without segmented electrodes.

It is apparent from the above that there exists a need in the art for a normally white liquid crystal display wherein the viewing zone of the display has both high contrast ratios and

little or no inversion over a wide range of viewing angles, the viewing zones position being shiftable to different vertical regions so as to allow viewers at such predetermined viewing angles (e.g. positive vertical viewing angles) to be able to satisfactorily view the displayed image.

This invention will now be described with respect to certain embodiments thereof, accompanied by certain illustrations wherein:

SUMMARY OF THE INVENTION

Generally speaking this invention fulfills the above-described needs in the art by providing a method of shifting the high contrast ratio viewing zone of a twisted nematic normally white liquid crystal display upward into the positive or upward vertical viewing zone, the method comprising the steps of:

a) sandwiching a twisted nematic liquid crystal layer between a pair of electrodes, the liquid crystal layer having a thickness of from about 4.5–6.5 μm;

b) orienting the liquid crystal molecules on a first side of the liquid crystal layer in a first direction;

c) orienting the liquid crystal molecules on a second side of the liquid crystal layer in a second direction, the first and second directions being different from one another in a manner such that the liquid crystal layer when in the off-state twists at least one visible wavelength of light less than about 100°;

d) providing a retardation film having a retardation value "d.Δn" in the range of about 100–250 nm on the first side of the liquid crystal layer, wherein "d" is the thickness of the retardation film and "Δn" is its birefringence;

e) rotating the optical axis of the retardation film from above 2°–20° relative to the second direction, the rotating of the optical axis shifting the high contrast viewing zone vertically so that viewers at such viewing angles may see a high contrast image with reduced inversion.

This invention further fulfills the above-described needs in the art by providing a twisted nematic liquid crystal display capable of displaying an image to a viewer, the display comprising:

a pair of electrodes sandwiching a twisted nematic liquid crystal layer therebetween, the pair of electrodes for applying a voltage across the liquid crystal layer;

first and second orientation means disposed adjacent the liquid crystal layer on opposite sides thereof, the first orientation means defining a first orientation or buffing direction and the second orientation means defining a second orientation or buffing direction, the first and second orientation directions for aligning the liquid crystal molecules of the liquid crystal layer in a predetermined manner;

a positively birefringent unaxial retardation film having a retardation value "d.Δn" in the range of about 100–200 nm, where "d" is the thickness of the retardation film and "Δn" is its birefringent value, wherein the retardation film is disposed on the same side of the liquid crystal layer as the first orientation means, the retardation film being oriented such that its optical axis is substantially parallel±about 20° to the second orientation or buffing direction of the second orientation means thereby enabling the liquid crystal display to display to the viewer an image with improved contrast ratios and reduced inversion.

This invention further fulfills the above-described needs in the art by providing a method of making a normally white twisted nematic liquid crystal display, a method comprising the steps of:

a) sandwiching a liquid crystal layer between first and second electrodes, the liquid crystal layer having a thickness "d" of from about 4.5 to 6.5 μm;

b) providing a first orientation means between the first electrode and the liquid crystal layer, the first orientation means for orienting LC molecules of the LC layer in a first direction adjacent the first orientation means;

c) providing a second orientation means between the LC layer and the second electrode, the second orientation means for orienting LC molecules in a second direction adjacent the second orientation means;

d) disposing a positively birefringent uniaxial retardation film on the same side of the LC layer as the first electrode and first orientation means, the retardation film having a retardation value of from about 100–200 nm; and

e) orientating the optical axis of the uniaxial retardation film substantially parallel±about 20° to the second direction defined by the second orientation means whereby the normally white display exhibits improved contrast ratios and reduced inversion.

This invention will now be described with respect to certain embodiments thereof, wherein:

IN THE DRAWINGS

FIG. 1 is a contrast ratio plot of a prior art light valve which utilized white light and an "on-state" driving voltage of about 6.8 volts.

FIG. 2 is an intensity versus driving voltage plot of the prior art light valve of FIG. 1, this plot illustrating a fairly large amount of undesireable inversion over a wide range of horizontal viewing angles at driving voltages greater than about 3 volts.

FIG. 3 is a graph illustrating the angular relationship between the horizontal and vertical viewing angles discussed herein, and their relationship with conventional liquid crystal display viewing angles: azimuthal angle ø; and polar angle Θ.

FIG. 4 is an exploded perspective schematical diagram of the optical components and their respective orientations of an LCD according to a first embodiment of this invention.

FIG. 5 is a top view illustrating the optical component angular relationships of the liquid crystal display of FIG. 4.

FIG. 6 is a side elevational cross-sectional view of the LCD of the first or FIGS. 4–5 embodiment of this invention.

FIG. 7 is an exploded perspective schematical diagram of the optical components and their respective orientations of an LCD according to a second embodiment of this invention, this embodiment being "P-buffed" as opposed to the "X-buffed" first embodiment.

FIG. 8 is an exploded perspective schematical diagram of the optical components and their respective orientations of an LCD according to a third embodiment of this invention wherein the retardation film is disposed on the rear or backlight side of the liquid crystal layer.

FIG. 9 is a white light contrast ratio contour plot of the normally white Display "A" of Example 1 when a driving voltage of about 6.8 volts was applied.

FIG. 10 is a white light contrast ratio contour plot of the normally white Display "A" of Example 1 when utilizing a driving voltage of about 6.0 volts was applied.

FIG. 11 is a white light transmission (fL) versus driving voltage plot of the normally white Display "A" of Example 1, this plot illustrating the viewing characteristics at a plurality of horizontal viewing angles disposed along the 0° vertical viewing axis.

FIG. 12(*a*) is a white light contrast ratio contour plot of the comparative normally white Display "B" of Example 1 when a driving voltage of about 6.8 volts was applied.

FIG. 12(*b*) is a white light contrast ratio contour plot of the comparative NW Display "C" of Example 1 when a driving voltage of about 6 volts was applied.

FIG. 13 is a white light contrast ratio contour plot of the NW light valve of Example 2 when a driving voltage of about 5.0 volts was applied.

FIG. 14 is a white light contrast ratio contour plot of the NW light valve of Example 2 when a driving voltage of about 4.0 volts was applied.

FIG. 15 is a white light contrast ratio contour plot of the normally white AMLCD of Example 3 when a driving voltage of about 6.0 volts was applied.

FIG. 16 is an exploded perspective schematical view of the optical components and their respective orientations of another embodiment of this invention wherein first and second retardation films (uniaxial or biaxial) are disposed on one side of the liquid crystal layer, as disclosed in U.S. Pat. No. 5,594,568 (Ser. No. 235,691), which was incorporated herein by reference above.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS OF THIS INVENTION

Referring now more particularly to the accompanying drawings in which like reference numerals indicate like parts.

FIG. 4 is an exploded schematic view of the optical components and their respective orientations of an LCD according to a first embodiment of this invention, the LCD being an AMLCD having a matrix array of pixels and colored subpixels in certain embodiments. As shown, this display (or display assembly) includes from the rear forward toward viewer 1, conventional backlight 3, rear or light-entrance linear polarizer 5, rear buffing or orientation film 7, liquid crystal layer 9, front buffing or orientation film 11, retardation film 13, and finally front or light-exit linear polarizer 15.

Backlight 3 is conventional in nature and emits substantially collimated or alternatively diffused light toward the display panel including rear polarizer 5 in certain embodiments of this invention. Backlight 3 may be, for example, the backlighting assembly disclosed in commonly owned U.S. Pat. No. 5,161,041, the disclosure of which is hereby incorporated herein by reference. Other conventional high intensity substantially collimated backlight assemblies may also be used.

Rear and front polarizers 5 and 15 are linear in nature in certain embodiments of this invention and their respective linear transmission axes P_R and P_F are orientated such that the displays of the different embodiments are of the normally white (NW) type. Therefore, when a driving voltage below the threshold voltage V_{th} is applied across liquid crystal layer 9, transmission axes P_R and P_F of polarizers 5 and 15 respectively are orientated such that the light emitted from backlight 3 proceeds through and is linearly polarized in direction P_R by polarizer 5, is then twisted (e.g. about 80°–100°) by LC material 9, and finally exits polarizer 15 via transmission axis P_F thus reaching viewer 1. The light reaches viewer 1 because its polarization direction upon reaching front polarizer 15 is similar to that of axis P_F. Thus, a NW display or pixel to which a voltage less than V_{th} is applied is said to be in the "off-state" and appears white (or colored if colored filters are present) to the viewer.

However, when a substantial driving voltage (e.g. about 6 volts) is applied across selected NW pixels of the matrix array including liquid crystal layer 9, the light transmitted through rear polarizer 5 is not significantly twisted by LC layer 9 and thus is substantially blocked by front polarizer 15 due to the fact that the polarization direction of light reaching the interior surface of front polarizer 15 is substantially perpendicular to transmission axis P_F thereby resulting in substantially no light reaching viewer 1 by way of the selected pixels to which the substantial driving voltage is applied. Thus, the selected pixels driven in the matrix array appear darkened to viewer 1, these pixels said to be in the "on-state". As will be appreciated by those of skill in the art, the amount of light reaching viewer 1 is dictated by the voltage applied to LC layer 9—the higher the driving voltage, the darker the selected driven pixel(s) appear.

In certain embodiments of this invention, transmission axis P_R of rear polarizer 5 and transmission axis P_F of front polarizer 15 are oriented in a manner substantially perpendicular to one another so as to define a normally white twisted nematic cell. However, polarizers 5 and 15 may be oriented in other conventional manners which also allow the cell or display to be of the normally white type.

Rear and front orientation or buffing films 7 and 11, respectively, are conventional and made of a substantially transparent polyimide in certain embodiments of this invention. Rear orientation film 7 is conventionally buffed or oriented in direction B_R as shown in FIG. 4. Likewise, front film 11 is conventionally buffed in direction B_F. Buffing directions B_R and B_F are oriented substantially perpendicular to one another in certain embodiments of this invention so as to allow the molecules of liquid crystal layer 9 when in the off or non-driven state to be twisted from about 80°–100°, most preferably about 90°. The term "off-state" means that a voltage below the threshold voltage (V_{th}) is applied across LC layer 9.

Due to the orientation of buffing directions B_R and B_F of orientation films 7 and 11 respectively, the polarization direction of normally incident light emitted from backlight 3 reaching liquid crystal material 9 is twisted in a conventional manner by the liquid crystal molecules as it passes through layer 9, when, of course, the display (or selected pixels thereof) is in the off-state.

However, when a substantially full driving voltage, e.g. about 6 volts or above, is applied to liquid crystal layer 9 (or selected pixels thereof to form the intended image), the normally incident light from backlight 3 reaching layer 9 is permitted to pass therethrough while substantially maintaining its initial direction of polarization. This is due to the fact that when a voltage is applied across LC material 9, the LC molecules are caused to become substantially aligned with one another in the vertical direction as shown in FIG. 4. Therefore, little or substantially no twisting occurs when such a driving voltage (e.g. about 6 volts) is applied and thus the direction of polarization of light passing through layer 9 is substantially maintained.

The voltage amount applied across LC layer 9 determines the degree of twisting of the liquid crystal molecules and thus dictates the polarization direction of light emitted from the front or viewer side of layer 9. In turn, the polarization direction of light reaching polarizer 15 dictates the amount of light permitted to pass therethrough via axis P_F and reach viewer 1 in that the closer aligned transmission axis P_F and the polarization direction of light reaching polarizer 15, the more light which is allowed to pass and reach viewer 1.

While the application of voltage $>V_{th}$ to layer 9 causes the LC molecule to substantially align vertically, the LC molecules never completely stand on end or become perfectly aligned in the vertical direction as is known in the art. This gives rise to the need for retardation film(s).

Retardation film 13 in this first embodiment is disposed on the viewer side of liquid crystal layer 9 thereby being sandwiched between front polarizer 15 and front orientation film 11. Surprisingly, it has been found that the provision of retardation film 13 on a single side of twisted nematic LC layer 9 reduces inversion and improves viewing zone contrast ratios at large viewing angles when the retardation value of the film is reduced relative to the prior art to retardation values of from about 100–200 nm.

Retardation film 13 in certain embodiments of this invention is positively birefringent and uniaxial in nature, this film being obtained from, for example, Nitto Corporation, Japan, or Nitto Denko America, Incorporated, New Brunswick, N.J. as Model No. NRF-140 (140 nm retarder).

Alternatively, it is believed that biaxial retardation films having similar retardation values may also provide excellent results, such biaxial retardation films and values being disclosed in aforementioned U.S. Ser. No. 08/235,691 filed Apr. 29, 1994.

With reference to FIGS. 4–5, axis P_R and direction B_F are substantially parallel to one another in certain embodiments of this invention while direction B_R, axis P_F, and direction R (or R_0) are also substantially parallel±about 5° to one another. Accordingly, in such embodiments, axis P_R and direction B_R are substantially perpendicular to one another as are axis P_F and direction B_F. A display having such an optical arrangement is said to be "X-buffed". The term "X-buffed" means that rear polarizer axis P_R is substantially perpendicular to rear buffing direction B_R while front polarizer axis P_F is substantially perpendicular to front buffing direction B_F. Thus, the first embodiment of this invention illustrated in FIGS. 4–6 is an LCD of the "X-buffed" type.

Alternatively, an LCD may be "P-buffed" instead of "X-buffed" in certain embodiments, "P-buffed" meaning that rear polarizer axis P_R is substantially parallel to rear buffing direction B_R and front polarizer axis P_F is substantially parallel to front buffing direction B_F.

Optical axis R of retardation film 13 in the first embodiment of this invention (see FIGS. 4–6) may be aligned in direction R_0 so as to be substantially parallel to axis P_F and buffing direction B_R. Alternatively, optical axis R of retardation film 13 may be rotated either clockwise or counterclockwise relative to directions R_0 and B_R.

The effect of rotating optical axis R of film 13 relative to direction R_0 is to shift the viewing zone or envelope of the display vertically into either the upper or lower vertical region as will be further discussed in the examples below. When film 13 is disposed forward of LC layer 9 and optical axis R of retardation film 13 is rotated clockwise relative to direction R_0 (as shown in FIGS. 4–5) so as to define angle e therebetween, the high contrast viewing envelope of the display is shifted into the upper or positive vertical region so as to provide viewer 1 with a high contrast ratio image at increased positive vertical viewing angles. To achieve such a high quality shifted image in the positive vertical region, optical axis R of retardation film 13 is rotated clockwise (to define ∂) from about 2°–20° relative to R_0, more preferably about 4°–15°, and most preferably from about 6°–10° in certain embodiments of this invention. The term "clockwise" is defined as being viewed from the position of viewer 1 in FIG. 4 (or as shown in FIGS. 4–5).

Alternatively, optical axis R of film 13 may be rotated counterclockwise relative to direction R_0 so as to shift the high contrast viewing envelope of the display into the negative vertical viewing region when film 13 is positioned forward of LC layer 9. The same degrees of rotation discussed above relative to clockwise rotation of axis R also apply to this alternative counterclockwise rotation of optical axis R relative to directions R_0 and B_R.

The ability to shift the viewing zone vertically via rotation of film 13 is advantageous in that it allows for excellent positive or negative vertical viewing characteristics in situations where they are needed. Thus, if a customer desires good positive vertical viewing, the manufacturer need simply rotate optical axis R of retardation film 13 in the clockwise direction as discussed above.

The retardation value "d.Δn" of retardation film 13 is a critical parameter in achieving the surprising results of the different embodiments of this invention, where "d" is the thickness of the retardation film and "Δn" is its birefringent value. In certain embodiments, retardation film 13 is of the uniaxial positively birefringent type and has a retardation value of from about 100–200 nm, more preferably from about 110–180 nm, and most preferably from about 120–160 nm. The biaxial retardation values of the biaxial retarders disclosed in Ser. No. 08/235,691 will also suffice in certain embodiments. In certain embodiments of this invention, as disclosed in U.S. Pat. No. 5,594,568 (i.e. Ser. No. 08/235,691) which was incorporated into this application by reference on page 1, first and second biaxial negative retarders, each having a retardation value $d.\Delta n_{ZY}$ of from about −10 to −100 nm, may be provided for improving the viewing characteristics of the display. In certain embodiments, the first and second negative biaxial retardation films or layers may be provided on the same side of the liquid crystal layer.

FIG. 6 is a side elevational cross-sectional view of the NW liquid crystal display of the first embodiment of this invention. As shown, the display includes the optical elements illustrated in FIGS. 4–5 as well as rear transparent substrate 17, front transparent substrate 19, rear electrode 21, and front electrode 23.

Transparent substrates 17 and 19 are made of glass or transparent plastic in certain embodiments of this invention, rear substrate 17 being sandwiched between rear polarizer 5 and rear electrode 21 and front transparent substrate 19 being disposed between front electrode 23 and retardation film 13. Alternatively, retardation film 13 may be disposed interior substrate 19 as opposed to its exterior position shown in FIG. 6.

Rear and front electrodes 21 and 23 are conventional in nature and made of transparent ITO in certain embodiments of this invention. While electrodes 21 and 23 are both shown in FIG. 6 as being continuous in nature, rear electrode 21 in AMLCD applications may be conventionally segmented into a number of different pixel or colored subpixel electrodes. In such AMLCDs, each pixel or colored subpixel may be individually addressed via a corresponding conventional a-Si TFT or diode.

For example, electrode 21 may be divided into thirty separate and independent subpixel electrodes, ten of which are associated with corresponding blue filters (not shown) so as to define blue subpixels, another ten of which are associated with corresponding red filters (not shown) thereby defining red subpixels, and the remaining ten being associated with green color filters (not shown) so as to define green subpixels. The color filters (not shown) are disposed on the opposing side of LC layer 9 with respect to the segmented

electrodes. In such an arrangement, the thirty subpixels may make up ten pixels, each pixel having a red, green, and blue subpixel therein arranged in a triangular fashion in certain embodiments.

With reference to FIGS. 4–6, in a typical operation of this first embodiment, the display operates as follows. White light is first emitted from conventional collimating backlight 3 and directed toward the rear side of the display panel. The light from backlight 3 hits rear polarizer 5 and is linearly polarized in accordance with polarization axes P_R. After being initially polarized, the linearly polarized light proceeds through rear transparent substrate 17, rear electrode(s) 21, and rear buffing or orientation film 7 before reaching liquid crystal layer 9.

When liquid crystal layer 9 is in the off-state, the light proceeding therethrough is twisted (preferably about 90°) before exiting layer 9 and reaching front buffing film 11. However, when LC layer 9 has a voltage (e.g. about 6 volts) above V_{th} applied thereto and is therefore in the on-state, the polarization direction of the light reaching its rear surface remains substantially unchanged as it proceeds through layer 9 and exits its front surface adjacent front orientation film 11 because the application of voltage across layer 9 causes the LC molecules thereof to become substantially aligned vertically or "stand up" as known in the art. Accordingly, the polarization direction of the light exiting LC layer 9 depends upon the voltage applied across the liquid crystal material—the higher the voltage, the more the LC molecules become aligned and the less twisting which occurs.

After exiting the front or exit side of liquid crystal layer 9, the light proceeds through front orientation film 11, front transparent ITO electrode 23, subpixel color filters (not shown) if present, and front transparent substrate 19 before reaching uniaxial retardation film 13. As the light proceeds through retardation film 13, the film conventionally introduces a phase delay that substantially restores the original polarization state of the light to what it was before it entered liquid crystal layer 9 (assuming the display is in the "on-state").

A need for retardation film 13 arises because when a driving voltage is applied across LC layer 9, the liquid crystal molecules become aligned vertically, but never completely. In other words, the liquid crystal molecules, even when a high driving voltage is applied thereto, are tilted slightly from the vertical. This inevitable tilting of the LC molecules creates the need for retardation film 13 which in effect produces a phase delay which reverses the effect caused by the non-perfect vertical alignment of the LC molecules.

After exiting retardation film 13, the light which originated from backlight 3 reaches the interior side of front linear polarizer 15. As discussed above, the polarization direction of the light reaching front polarizer 15 depends upon the driving voltage (or absence thereof) applied across liquid crystal layer 9. Thus, with respect to LC pixels of the matrix array in the off-state, the polarization direction of light reaching front polarizer 15 is substantially aligned with transmission axis P_F which results in these off-state pixels appearing white or colored to the viewer.

However, with respect to on-state pixels in which a driving voltage $>V_{th}$ is applied across LC material 9, the polarization direction of light reaching front polarizer 15 is not substantially aligned with transmission axis P_F thus resulting in on-state pixels appearing darkened to viewer 1 because polarizer 15 substantially blocks the light from reaching viewer 1. In such a manner, the application of

predetermined driving voltages to selective pixels or colored subpixels results in desired images being displayed to viewer 1.

FIG. 7 is an exploded schematic view of the optical components and their respective orientations of an LCD according to a second embodiment of this invention. This second embodiment depicted in FIG. 7 differs from the first embodiment (FIGS. 4–6) in that the first embodiment is "X-buffed" and this second embodiment is "P-buffed". In other words, transmission axis P_R of rear linear polarizer 5 in this embodiment is substantially parallel to buffing direction B_R of rear orientation film 7, and transmission axis P_F of front polarizer 15 is substantially parallel to buffing direction B_F of front orientation film 11, thus defining a "P-buffed" display.

As will be appreciated by those of skill in the art, the display of the first embodiment may be adjusted so as to be transformed into the LCD of the second embodiment simply by rotating rear and front polarizers 5 and 15 respectively about 90° each, the rest of the cell such as LC layer 9, orientation films 7 and 11, retardation film 13, substrates 17 and 19, and electrodes 21 and 23 remaining substantially the same in both the first and second embodiments.

FIG. 8 is an exploded schematic view of the optical components and their respective orientations of an "X-buffed" LCD according to a third embodiment of this invention. While both the first and third embodiments illustrated and described herein are "X-buffed", the principal difference therebetween is the position of retardation film 13. As shown in FIG. 8, retardation film 13 is disposed rearward or on the backlight side of liquid crystal layer 9 as opposed to its disposition on the front side thereof in the first embodiment of this invention.

A significant advantage associated with the positioning of retardation film 13 rearward of liquid crystal layer 9 is the reduction of ambient light reflection off of the front of the display panel, this reduction being attributed to fewer mismatching indices of refraction forward of liquid crystal layer 9 as discussed in aforesaid Ser. No. 08/235,691.

With respect to the third embodiment shown in FIG. 8, optical axis R of retardation film 13 may be rotated clockwise or counterclockwise relative to direction R_0 and buffing direction B_F, counterclockwise rotation causing the viewing envelope to shift into the upper or positive vertical region as in the first embodiment and clockwise rotation causing the envelope to shift into the negative or lower vertical viewing region. Therefore, if film 13 is disposed on the viewer side of liquid crystal layer 9, it must be rotated clockwise in order to shift the viewing envelope into the upper or positive vertical region, while if retardation film 13 is disposed rearward of liquid crystal layer 9 as in FIG. 8, counterclockwise rotation of optical axis R relative to directions R_0 and B_F as shown in FIG. 8 will cause the viewing envelope to shift into the upper vertical region.

With respect to the optical components of the third embodiment, transmission axis P_R of rear polarizer 5 is substantially parallel to direction R_0 and buffing direction B_F. Likewise, transmission axis P_F of front polarizer 15 is substantially parallel to buffing direction B_R of rear orientation film 7, buffing directions B_F and B_R being substantially perpendicular to one another. With respect to the retardation value of retarder 13, each of the first, second, and third embodiments utilize the aforediscussed retardation values.

This invention will now be described with respect to certain examples as follows:

EXAMPLE 1

In this first Example, three separate normally white a-Si TFT driven twisted nematic AMLCDs were manufactured and tested for purposes of comparison. The three AMLCDs are referred to in this Example as Display "A", Display "B", and Display "C" respectively. Each of the three AMLCDs of this Example utilized the same liquid crystal layer, RGB color filters, orientation films, electrodes, and transparent substrates. In other words, Displays "B" and "C" were constructed simply by adjusting or replacing the polarizers and/or retardation film 13.

The liquid crystal material of each display had a birefringence (ΔN) of about 0.084 at room temperature and was obtained from E. Merck Ltd. or its United States representative E. M. Industries, Inc., Hawthorne, N.Y. as Model No. ZLI-4718. Each of the three displays was tested at about 35°–45° C. The electrodes were conventional in nature and made of transparent ITO, the substrates were made of glass, and the buffing or orientation films were conventional in nature and made of a polyimide material. All three NW AMLCDs of this Example were of the RGB colored type and had red cell gaps "d" of about 5.6 μm, and green and blue cell gaps of about 5.3 μm, each pixel having a triad arrangement of RGB subpixels. White light emitted from conventional backlight 3 was utilized in all Examples herein.

The optical construction of Display "A" of this first Example is shown in FIGS. 4–6. NW Display "A" included from the rear forward toward viewer 1, conventional backlight 3, conventional linear polarizer 5 with transmission axis P_R, rear transparent glass substrate 17, rear segmented pixel and RGB subpixel electrodes 21, rear orientation film 7 having buffing direction B_R, liquid crystal layer 9, front orientation film 11 having buffing direction B_F, front electrode 23, RGB color filters (not shown) corresponding to each subpixel segment of electrode 21, front transparent glass substrate 19, uniaxial positively birefringent retardation film 13 having optical axis R, and finally front linear polarizer 15 having transmission axis P_F.

With respect to Display "A", transmission axis P_R of rear polarizer 5 was substantially parallel to buffing direction B_F of front orientation film 11. Also, transmission axis P_F of front polarizer 15 was substantially parallel to rear buffing direction B_R of orientation film 7 thus defining an "X-buffed" AMLCD, buffing directions B_F and B_R being substantially perpendicular to one another.

Retardation film 13 was positively birefringent and had a retardation value of 140 nm. Optical axis R of retardation film 13 was rotated about 8.5° in the clockwise direction relative to axis P_F and direction B_R so as to define Θ as shown in FIGS. 4–5 as about 8.5°. Retardation film 13 of Display "A" was obtained from Nitto Corporation, Japan, or Nitto Denko America, New Brunswick, N.J., as Model No. NRF140.

Rear and front linear polarizers 5 and 15 of all Examples herein were conventional in nature and obtained from Nitto Denko America, Model No. G 1220DUN.

FIG. 9 is a contrast ratio contour plot of Display "A" of this Example when a driving voltage of about 6.8 volts was applied thereto and white light was emitted from backlight 3. As shown, the high contrast viewing zone was shifted vertically into the positive vertical region (above the 0° vertical viewing axis) by the aforesaid clockwise rotation of optical axis R of retardation film 13. This display had at least about a 10:1 contrast ratio at +10° vertical over a total range of about 110° horizontal, this being an improvement of about 40° with respect to the light valve of prior art FIG. 1 at the same 10° vertical viewing axis. In a similar manner, Display "A" had at least about a 10:1 contrast ratio at +50° vertical that extended over a total of about 95° horizontal, this 95° horizontal range being a significant improvement over the contrast ratio at 50° vertical with respect to the light valve of FIG. 1.

As shown, the viewing zone or envelope of Display "A" when about 6.8 volts was applied thereto was fairly uniform (or unskewed) in nature. Additionally, high contrast ratios (e.g. 50:1) of Display "A" extended over significantly greater horizontal and vertical expanses than did their corresponding ratios in the light valve of prior art FIG. 1. For Example, the 50:1 contrast ratio of Display "A" at +10° vertical extended over a total of about 80° horizontal as shown in FIG. 9, while the corresponding 50:1 contrast ratio curve in prior art FIG. 1 at 10° vertical extended only over about 40° horizontal. Thus, it is evident that the addition of retardation film 13 with its corresponding retardation value and optical orientation resulted in a significant improvement with respect to contrast ratio.

FIG. 10 is a contrast ratio contour plot of Display "A" of this Example when about a 6.0 volt driving voltage was applied thereto. As shown, the slight reduction in driving voltage resulted in the contrast ratio contours slightly shrinking horizontally in the extreme upper vertical viewing region (e.g. 60° vertical).

FIG. 11 is an intensity (fL) vs driving voltage plot of Display "A". As shown, Display "A" had significantly reduced inversion with respect to that of the prior art light valve shown in FIG. 2. This is evident by the substantial elimination of the prior art inversion humps present at about 3.0 volts and greater. No such inversion humps are shown in FIG. 11 thus illustrating the significant improvement over the prior art with respect to inversion at the illustrated horizontal viewing angles along the 0° vertical viewing axis. The elimination of the inversion humps of the prior art allows Display "A" to be easily and effectively driven with a plurality of gray level driving voltages while allowing viewers at different viewing angles to see substantially the same image with respect to color and other important viewing characteristics.

FIG. 12(a) is a contrast ratio contour plot of NW a-Si TFT driven "X-buffed" Display "B" of this Example, Display "B" being manufactured and tested for purposes of comparison with Display "A". As stated above, Display "B" was manufactured utilizing the same liquid crystal material, electrodes, RGB color filters, orientation films, TFTs, and transparent substrates as Display "A". The only difference between Display "A" and Display "B" was that the retardation value of uniaxial positively birefringent retardation film 13 of Display "B" was about 350 nm instead of the 140 nm value of Display "A" and optical axis R of retardation film 13 was substantially parallel to directions R_0 and B_R. Thus, by comparing the results of displays "A" and "B", one may easily see the improvement resulting from the use of a retardation value in the range of about 100–200 nm (e.g. 140 nm) as opposed to retardation values greater than about 300 nm.

As shown in FIG. 12(a) the high contrast viewing envelope of the 350 nm retardation film Display "B" was significantly smaller with respect to contrast ratio than was that of Display "A" shown in FIG. 9. By comparing FIGS. 9 and 12(a), it is clear that use of the higher value retardation film resulted in a smaller viewing envelope both vertically and horizontally.

Further evident from comparing FIGS. 9 and 12(*a*) is the fact that Display "A" had higher contrast ratios (e.g. 50:1 and greater) over a larger range of viewing angles than did Display "B" thus resulting in improved viewing characteristics. Thus, this additional advantage associated with the lower value retardation film is clear.

FIG. 12(*b*) is a contrast ratio contour plot of NW a-Si TFT driven Display "C" of this Example. Display "C" differed from Display "A" in that Display "C" was "P-buffed" as shown in FIG. 7 (instead of "X-buffed") and utilized a uniaxial positively birefringent retardation film 13 having a retardation value of about 350 nm. Furthermore, optical axis R of retardation film 13 in Display "C" was substantially parallel to axis P_R and direction B_R (Θ=about 0°).

All three NW AMLCDs of this Example had their respective retardation films disposed on the forward or viewer side of liquid crystal material 9 and sandwiched between front substrate 19 and front polarizer 15.

Display "C", which is similar to NW displays described in U.S. Pat. No. 5,184,236, had its contrast ratio contour plot illustrated when about 6.0 volts was applied thereto in FIG. 12(*b*). As shown in FIG. 12(*b*) as compared to FIG. 9, Display "C" had significantly lower contrast ratio expanses both vertically and horizontally than did Display "A". Additionally, the extent of higher contrast ratios (e.g. 50:1) in Display "A" was greater than that of Display "C" as is evident by comparing FIG. 9 with FIG. 12(*b*).

The orientations of retardation film optical axis R in Displays. "A", "B", and "C", of course, resulted in the viewing envelopes of Displays "B" and "C" not being shifted vertically as was the envelope of Display "A".

EXAMPLE 2

A "P-buffed" normally white twisted nematic light valve was manufactured and tested at about 35°–40° C. in this Example. This light valve had optical orientations similar to those shown in FIG. 7 and included from the rear forward toward viewer 1 conventional backlight 3, rear linear polarizer 5 with transmission axis P_R, rear transparent glass substrate 17, rear continuous electrode 21, rear orientation film 7 with buffing direction B_R, liquid crystal layer 9 having a thickness or cell gap "d" of about 5.86 μm, front orientation film 11 with buffing direction B_F, front continuous electrode 23, front transparent glass substrate 19, uniaxial positively birefringent retardation film 13 having a retardation value of about 120 nm, and finally front linear polarizer 15 having transmission axis P_F.

Retardation film 13 had its optical axis R rotated clockwise about 20° relative to directions R_0 and B_R so as to shift the viewing envelope into the positive vertical viewing region. In other words, Θ equaled about 20° as shown in FIG. 7.

Retardation film 13 of this Example was positively birefringent, uniaxial, and was obtained from Nitto Denko America, New Brunswick, N.J., Model No. NRF120. The liquid crystal material was identical to the type utilized in the displays of Example 1, as were the polyimide orientation films, glass substrates, and polarizers. Because this Example utilized a light valve, both electrodes 21 and 23 were continuous in nature as opposed to the segmented design of the rear electrode of each AMLCD in Example 1.

FIG. 13 is a contrast ratio contour plot of the NW light valve of Example 2 when about a 5.0 volt driving voltage was applied thereto. As shown, the 20° clockwise rotation of optical axis R of retardation film 13 resulted in the shifting of the viewing zone or envelope into the positive vertical region as is evident by FIG. 13. Furthermore, the use of the 120 nm retardation film resulted in high contrast ratios over a wide range of horizontal and vertical viewing angles as shown. Thus, the advantages of such a retardation value and the 20° rotation of optical axis R are self-evident in view of the superior viewing characteristics exhibited.

FIG. 14 is a contrast ratio contour plot of the NW light valve of this Example when about a 4.0 volt driving voltage was applied. As shown, the viewing zone remained in the upper or positive vertical region and was substantially uniform and unskewed in nature.

An advantage of particular interest associated with the light valve of this Example is its good contrast at driving voltages of about 4–5 volts. Certain driver chips often do not allow displays to be driven above 6 volts. In other words, such chips provide for maximum driving voltages of only about 6 volts, this meaning that many of the gray level driving voltages are around 4–6 volts. Therefore, the superior contrast behavior of this light valve at such driving voltages is a distinct advantage. The better behavior of this light valve at lower driving voltages is clearly an improvement over the prior art.

EXAMPLE 3

A normally white a-Si TFT driven twisted nematic AMLCD of the P-buffed type was manufactured and tested at about 35°–40° C. in this Example. The liquid crystal material was the same as discussed above in Examples 1 and 2, with this AMLCD having a cell gap "d" of about 5.3 μm in each of the red, green, and blue subpixels. Each pixel of this AMLCD included an RGB triad of subpixels. Unlike the other Examples herein, this AMLCD was driven with a conventional Gross Tester in that all column and row address lines were driven together.

As shown generally in FIG. 7, the AMLCD of Example 3 included from the rear forward conventional backlight 3, conventional polarizer 5 having transmission axis P_R, transparent rear glass substrate 17, transparent ITO segmented subpixel or pixel electrodes 21, rear orientation film 7 having buffing direction B_R, liquid crystal layer 9 having a RGB cell gap of about 5.3 μm, front orientation film 11 with buffing direction B_F, front continuous electrode 23, red, green, and blue color filters (not shown) corresponding to each subpixel electrode segment, front transparent glass substrate 19, uniaxial positively birefringent retardation film 13 having a retardation value of about 140 nm, and finally front linear polarizer 15 having transmission axis P_F.

Retardation film 13 was again obtained from Nitto Denko America, New Brunswick, N.J., as Model No. NRF140 and was oriented such that its optical axis R was rotated clockwise about 5° relative to direction B_R and axis P. In other words, e as shown in FIG. 7 was about 5°.

As shown in FIG. 15, the AMLCD of this Example had its viewing zone or envelope shifted into the positive vertical region by the 5° rotation of retardation film axis R, the viewing envelope being substantially uniform in nature as shown.

This concludes the Examples herein.

As is evident from the results of the aforesaid Examples, the provision of a retardation film having a retardation value of from about 100–200 nm (or 100–250 nm) on a single side of the liquid crystal layer significantly improves the viewing characteristics of a display with respect to both contrast ratio and inversion. As will be appreciated by those of skill in the art, the provision of a normally white twisted nematic LCD having an enlarged and vertically shiftable viewing zone

with reduced inversion is a significant improvement over conventional normally white LCDs, this improvement allowing the substantially cheaper to manufacture NW displays to take the place of more expensive normally black displays.

Furthermore, the ability to shift the viewing zone vertically into either the positive or negative vertical viewing region allows the manufacturer to custom make or tailor each AMLCD according to the needs of specific customers. For Example, one customer may require an AMLCD to be mounted in the lower portion of an avionic cockpit such that the pilot is forever looking downward at the display thus requiring the AMLCD to have high contrast ratios and reduced inversion in the upper or positive vertical region. In such a case, the desired viewing characteristics may be achieved simply by rotation of retardation film 13 as discussed above. Thus, the designs of the different embodiments of this invention allow different specifications to be realized.

FIG. 16 illustrates another embodiment of this invention where first and second biaxial (or uniaxial) retarders are located on the rear side of the liquid crystal layer. Such an embodiment is further described and illustrated in U.S. Pat. No. 5,594,568, incorporated herein by reference above. Alternatively, the two biaxial retarders may be located on opposite sides of the liquid crystal layer as described and illustrated in U.S. Pat. No. 5,570,214, also incorporated herein by reference above.

The pre-tilt angle of the displays and light valves herein may be about 3° in certain embodiments, and the value of "d/p" (thickness/natural pitch of the liquid crystal material) of the liquid crystal layers may be set to about 0.25.

Once given the above disclosure, many other features, modifications, and improvements will become apparent to the skilled artisan. Such other features, modifications, and improvements are, therefore, considered to be a part of this invention, the scope of which is to be determined by the following claims:

We claim:

1. A liquid crystal display capable of displaying an image to a viewer, the display comprising:

a pair of electrodes sandwiching a liquid crystal layer therebetween, said pair of electrodes for applying a voltage across said liquid crystal layer;

first and second polarizers sandwiching said liquid crystal layer therebetween;

first and second orientation layers disposed adjacent said liquid crystal layer on opposite sides thereof, said first and second orientation layers for aligning liquid crystal molecules of said liquid crystal layer;

first and second negative biaxial retardation members, wherein each of said first and second negative biaxial retardation members has a retardation value $d.\Delta n_{ZY}$ of from about −10 to −100 nm where "d" is the thickness of the retardation member; and

wherein at least a portion of each of said first and second negative biaxial retardation members has indices of refraction n_x, n_y, and n_z where n_z is oriented in a direction perpendicular to n_x and n_y.

2. A liquid crystal display for displaying an image to a viewer, the liquid crystal display comprising:

a liquid crystal layer disposed between first and second electrodes, said first and second electrodes for applying a voltage across said liquid crystal layer;

first and second polarizers, said liquid crystal layer being located between said first and second polarizers;

first and second orientation layers, said liquid crystal layer being located between said first and second orientation layers;

first and second negative retarders located on opposite sides of said liquid crystal layer so that said liquid crystal layer is disposed between said first and second negative retarders, each of said first and second negative retarders including three different and unequal indices of refraction;

wherein each of said negative retarders includes a retardation value $d.\Delta_{ZY}$ of from about −10 to −100 nm, where the retardation value is defined by the thickness of the retarder multiplied by a difference between two of said three indices of refraction; and

wherein said retarders are so arranged with respect to one another so that the display can achieve a white light contrast ratio of at least about 10:1 over a horizontal viewing angular span, at a predetermined vertical viewing angle, of at least about 120°, and over a vertical viewing angular span of greater than about 60° at a predetermined horizontal viewing angle.

3. The liquid crystal display of claim 2, wherein said first, second, and third indices of refraction are termed n_x, n_y, and n_z, wherein n_x and n_y define a plane and n_z is oriented in a direction perpendicular to said plane.

4. The display of claim 3, wherein said plane is parallel to planes defined by each of said first and second negative retarders.

* * * * *

TAB 4

US006229588B1

(12) **United States Patent**
Abileah et al.

(10) **Patent No.: US 6,229,588 B1**
(45) **Date of Patent: *May 8, 2001**

(54) **NORMALLY WHITE LCD INCLUDING FIRST AND SECOND BIAXIAL RETARDERS**

(75) Inventors: **Adiel Abileah**, Farmington Hills; **Gang Xu**, Royal Oak, both of MI (US)

(73) Assignee: **OIS Optical Imaging Systems, Inc.**, Troy, MI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/048,322**

(22) Filed: **Mar. 26, 1998**

Related U.S. Application Data

(63) Continuation of application No. 08/747,671, filed on Nov. 12, 1996, now Pat. No. 5,737,048, which is a continuation of application No. 08/255,971, filed on Jun. 8, 1994, now Pat. No. 5,576,861, which is a continuation-in-part of application No. 08/235,691, filed on Apr. 29, 1994, now Pat. No. 5,594,568, and a continuation-in-part of application No. 08/167,652, filed on Dec. 15, 1993, now Pat. No. 5,570,214.

(51) **Int. Cl.**[7] **G02F 1/1335**
(52) **U.S. Cl.** **349/120**; 349/119
(58) **Field of Search** 349/117, 119, 349/120, 118

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,900,248	8/1975	Nagasaki	349/81
4,385,806	5/1983	Fergason	349/34
4,436,379	3/1984	Funada et al.	349/75
4,632,514	12/1986	Ogawa et al.	349/160
4,652,088	3/1987	Kando et al.	349/101
4,674,841	6/1987	Buzak	349/97
4,686,519	8/1987	Yoshida et al.	349/95

(List continued on next page.)

FOREIGN PATENT DOCUMENTS

0349900	1/1990	(EP) .
0367616	5/1990	(EP) .
0576931	1/1994	(EP) .
0679921	11/1995	(EP) .
0774682	5/1997	(EP) .
55-45037	3/1980	(JP) .
63-239421 *	10/1988	(JP) .
313916	1/1991	(JP) .
3-69915 *	3/1991	(JP) .

OTHER PUBLICATIONS

"Wide Viewing Angle LCD Using Retardation Films" By Yamagishi, Watanabe and Yokoyama.

"Phase Difference Plate And Liquid Crystal Electro-Optical Device Using This Plate" by Okumura.

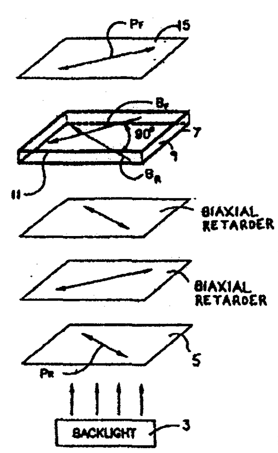
(List continued on next page.)

Primary Examiner—William L. Sikes
Assistant Examiner—Dung Nguyen
(74) *Attorney, Agent, or Firm*—Laff, Whitesel & Saret, Ltd.

(57) **ABSTRACT**

A normally white liquid crystal display is provided with a positively birefringent uniaxial retardation film having a retardation value of from about 100–200 nm. The retardation film is provided on one side of the liquid crystal layer, the liquid crystal being sandwiched between a pair of orientation or buffing films which orient the liquid crystal molecules adjacent thereto in predetermined directions. The optical axis of the retardation film is rotated from about 2°–20°, most preferably from about 6°–10° relative to the buffing direction on the opposite side of the liquid crystal layer. This rotation of the retardation film optical axis allows for the high contrast ratio viewing zone of the display to be shifted vertically into either the positive or negative vertical viewing region depending upon the direction of rotation of the retardation film optical axis. Alternatively, biaxial retardation films having similar retardation values may be utilized according to the teachings of this invention.

8 Claims, 16 Drawing Sheets



U.S. PATENT DOCUMENTS

4,693,562	9/1987	Hasegawa et al.	349/180
4,701,028	10/1987	Clerc et al.	349/98
4,844,569	7/1989	Wada et al.	349/117
4,852,976	8/1989	Suzuki	349/119
4,889,412	12/1989	Clerc et al.	349/118
4,957,349	9/1990	Clerc et al.	349/106
4,973,137	11/1990	Kozaki	349/119
4,984,873	1/1991	Takiguchi et al.	349/101
4,984,874	1/1991	Yamamoto et al.	349/119
4,991,941	2/1991	Kalmanash	349/33
4,995,704	2/1991	Yamamoto et al.	349/119
5,018,839	5/1991	Yamamoto et al.	349/121
5,032,008	7/1991	Yamamoto et al.	349/119
5,071,997	12/1991	Harris	528/353
5,107,356	4/1992	Castleberry	349/119
5,124,824	6/1992	Kozaki et al.	349/120
5,132,826	7/1992	Johnson et al.	349/80
5,138,474	8/1992	Arakawa	349/120
5,150,235	9/1992	Haim et al.	349/117
5,150,237	9/1992	Iimura et al.	349/118
5,157,529	10/1992	Koopman et al.	349/117
5,179,457	1/1993	Hirataka et al.	349/119
5,184,236	2/1993	Miyashita et al.	349/102
5,189,538	2/1993	Arakawa	349/118
5,194,975	3/1993	Akatsuka et al.	349/119
5,196,953	3/1993	Yeh et al.	349/119
5,227,903	7/1993	Miyazawa et al.	349/118
5,229,039	7/1993	Ikeda et al.	349/106
5,231,521	7/1993	Johnson et al.	349/77
5,237,438	8/1993	Miyashita	349/119
5,241,408 *	8/1993	Ishikawa et al.	349/117
5,250,214	10/1993	Kanemoto et al.	349/76
5,344,916	9/1994	Harris et al.	349/120
5,369,513	11/1994	Akatsuka et al.	349/118
5,448,386 *	9/1995	Watanabe et al.	349/119
5,548,426 *	8/1996	Miyashita et al.	349/117
5,570,214	10/1996	Abileah et al.	349/117
5,594,568	1/1997	Abileah et al.	349/119

OTHER PUBLICATIONS

"Liquid Crystal Display Device" By Watanabe.
"The Symmetry Property Of A 90 Degree Twisted Nematic Liquid Crystal Cell" By Lien.
Patent Abstracts of Japan, 07253573, Mar. 10, 1995.
WO 96/15473, Pub. Date May 23, 1996—PCT.

* cited by examiner

FIG. 1 (Prior Art)

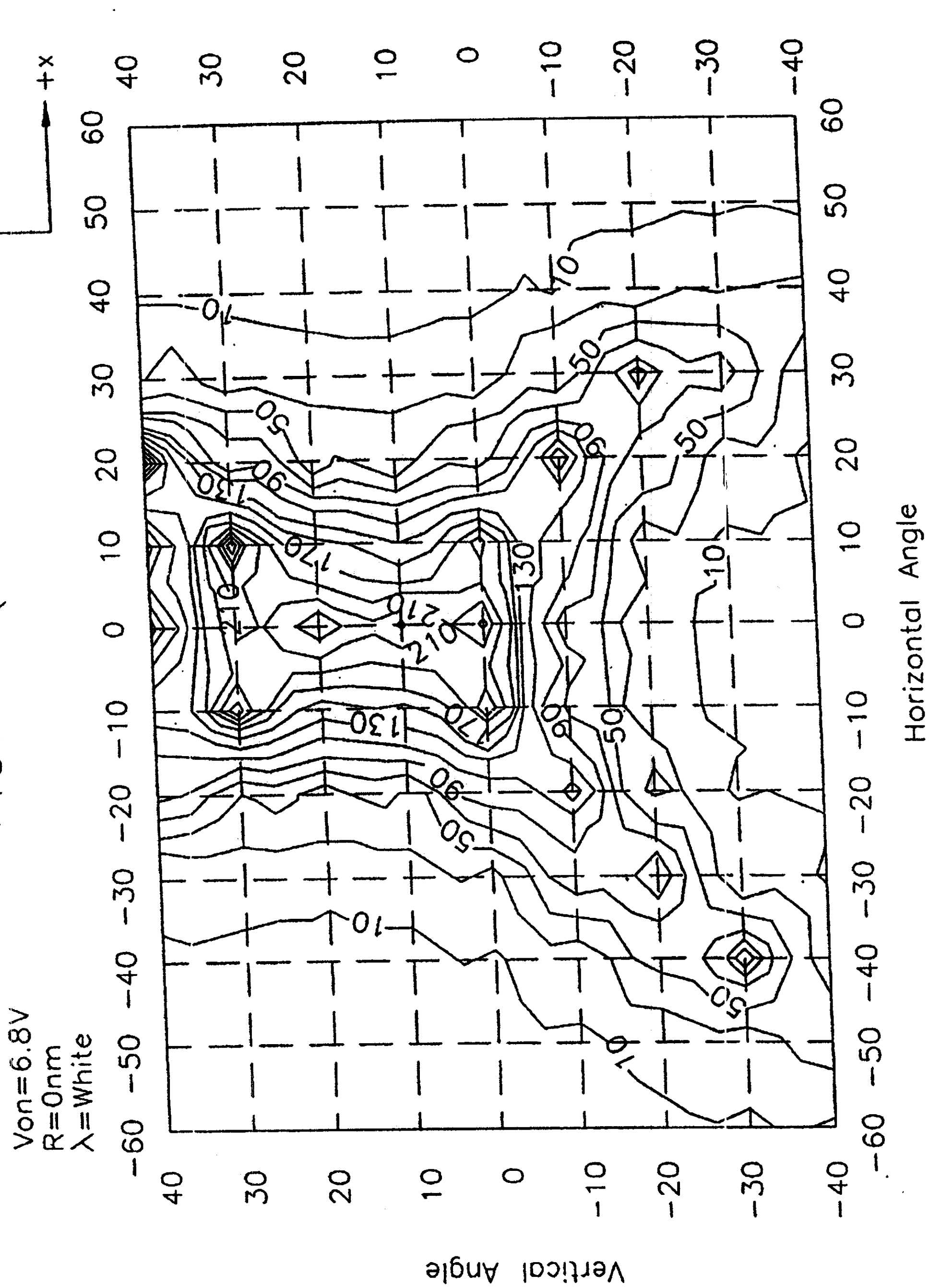
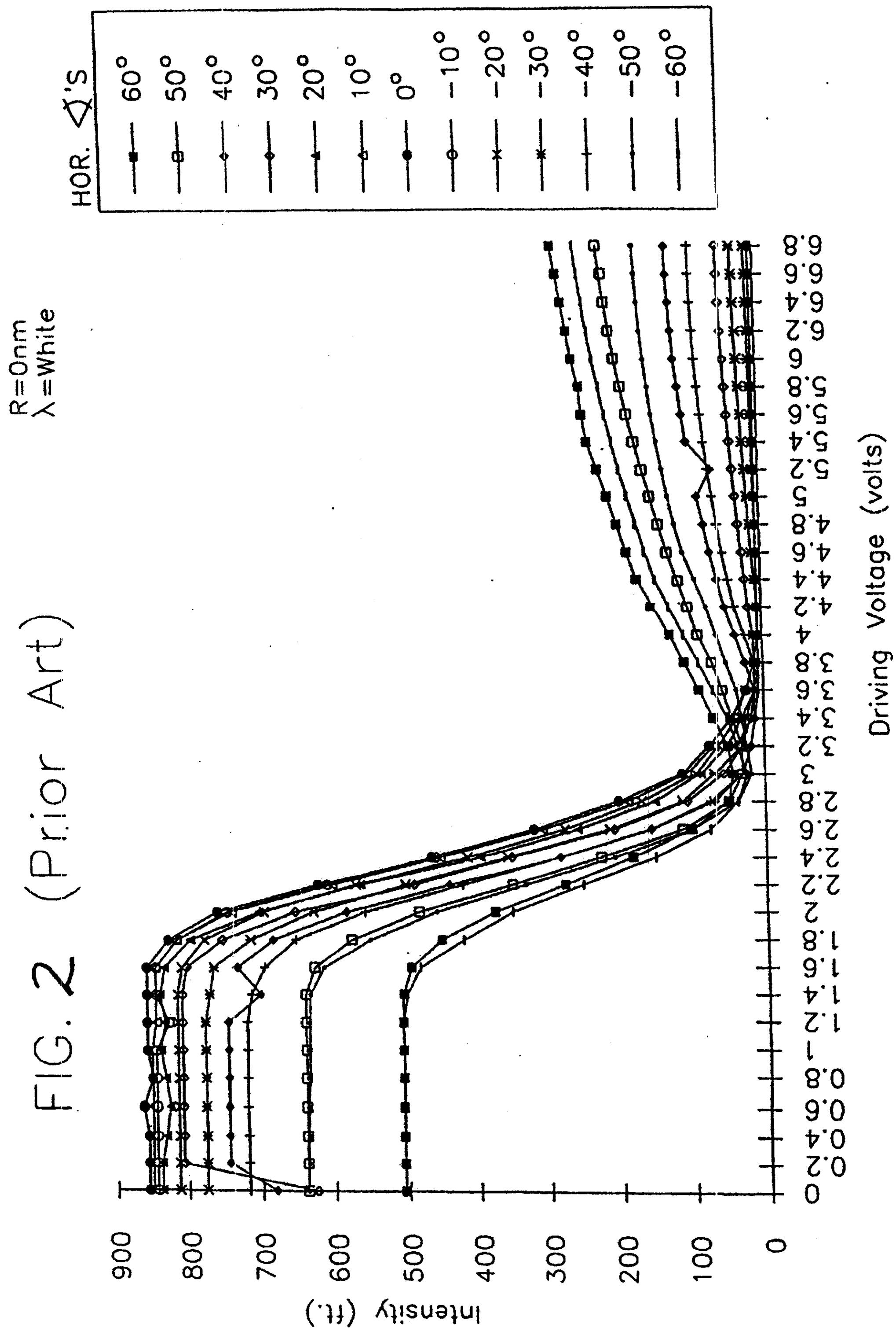


FIG. 2 (Prior Art)



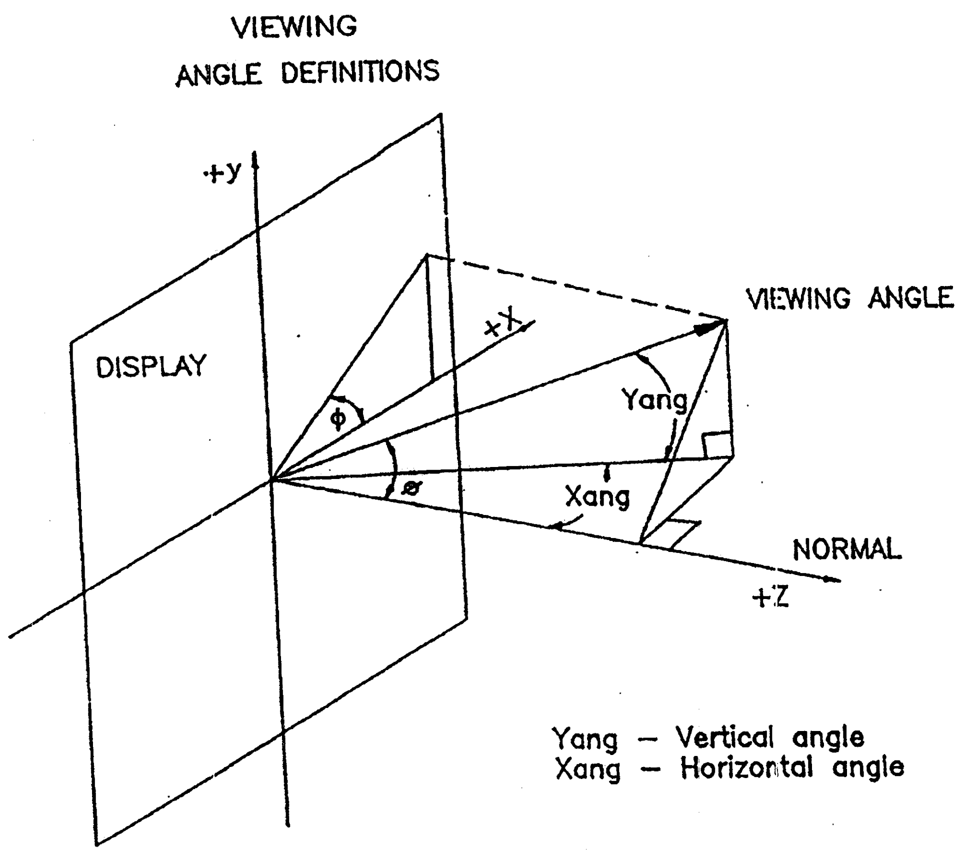

VIEWING
ANGLE DEFINITIONS
+y
DISPLAY
+X
VIEWING ANGLE
ϕ
Yang
Xang
NORMAL
+Z
Yang — Vertical angle
Xang — Horizontal angle

Fig. 3

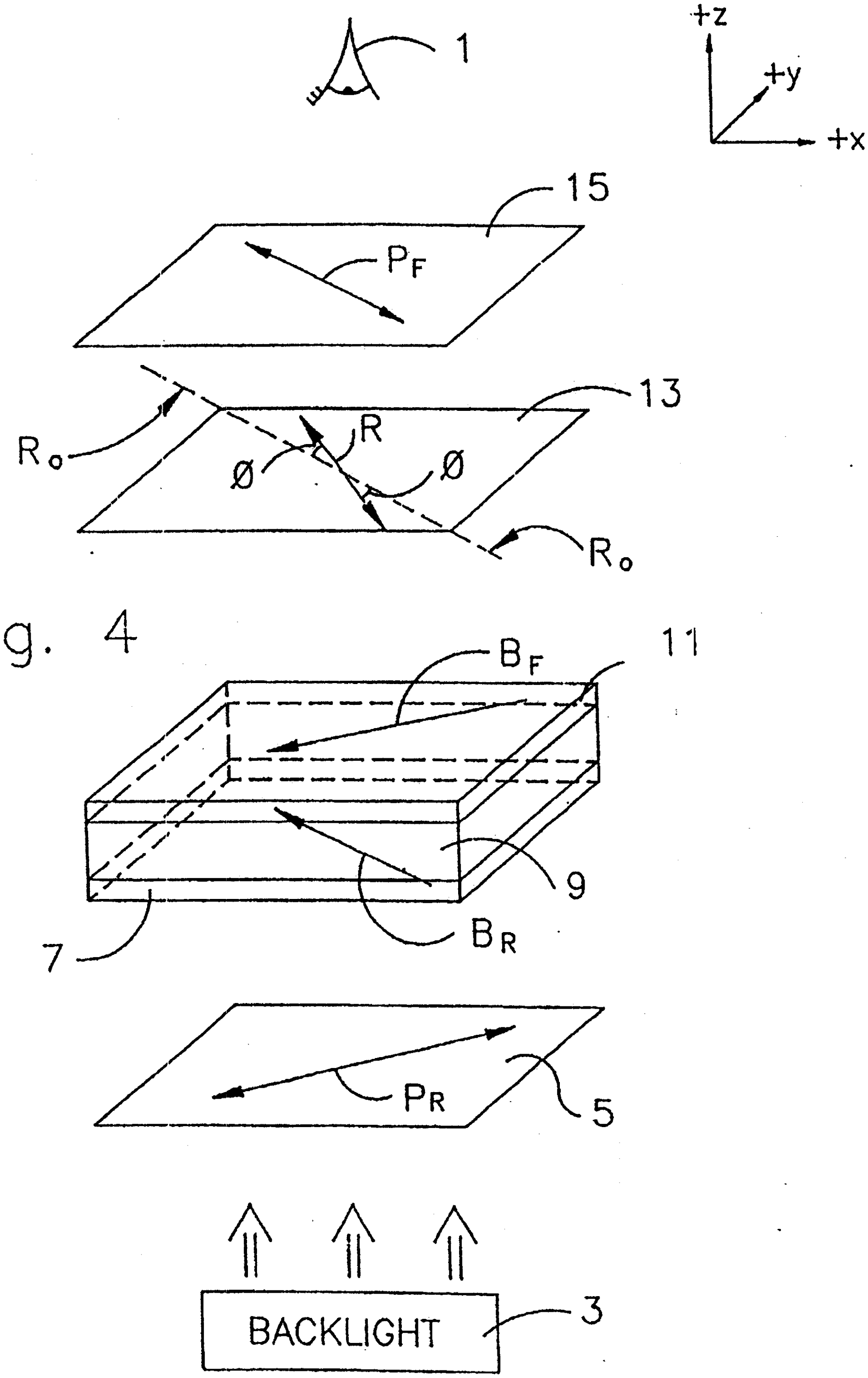
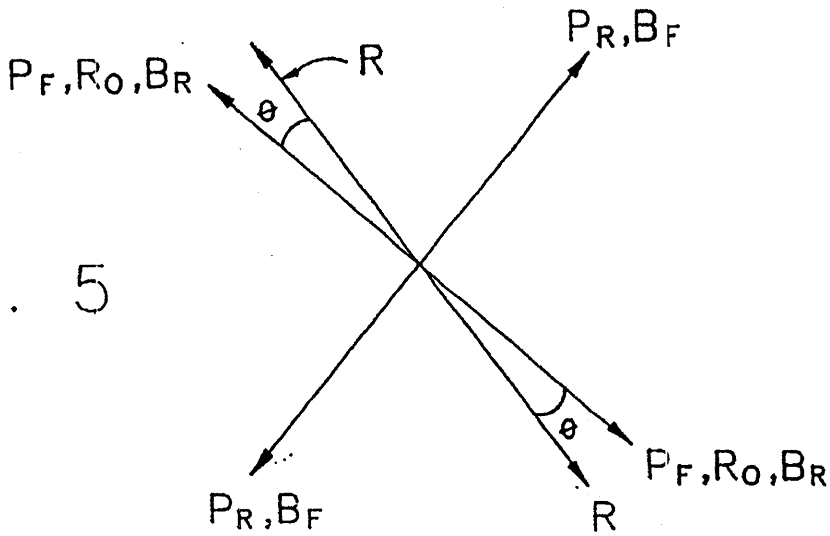
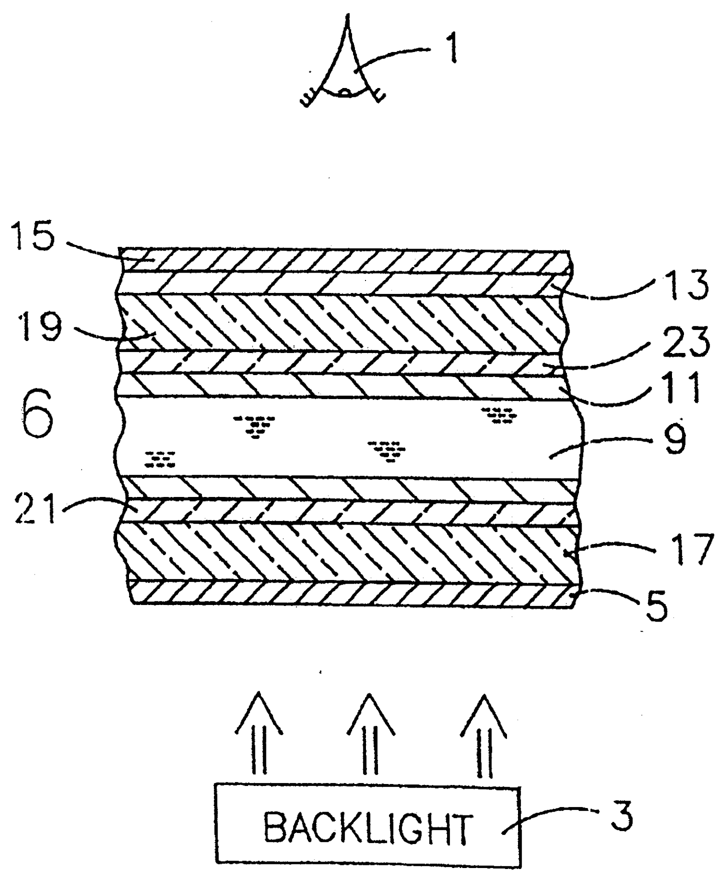


Fig. 4



P_F, R_O, B_R
R
P_R, B_F
θ
θ
P_R, B_F
R
P_F, R_O, B_R

Fig. 5



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9
21
17
5
BACKLIGHT
3

Fig. 6

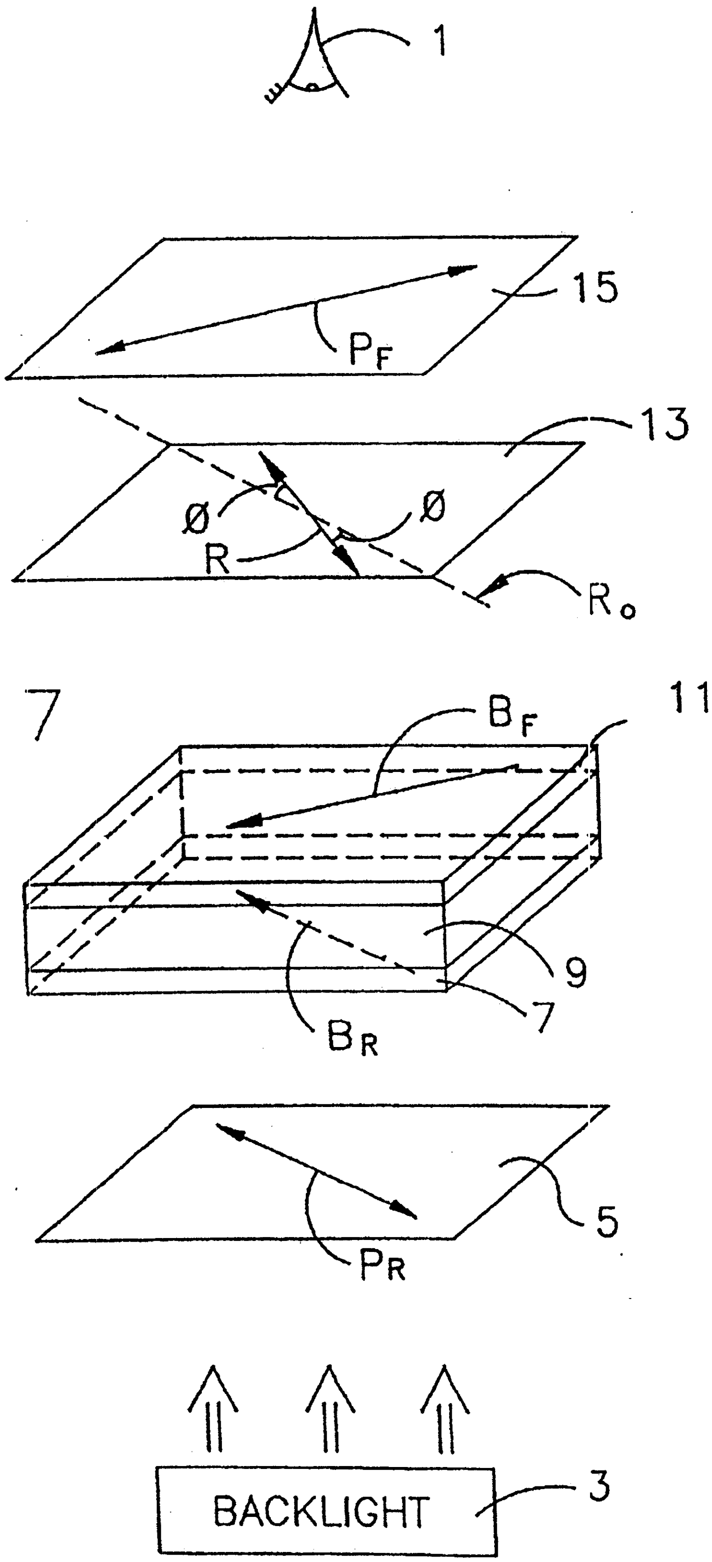


Fig. 7

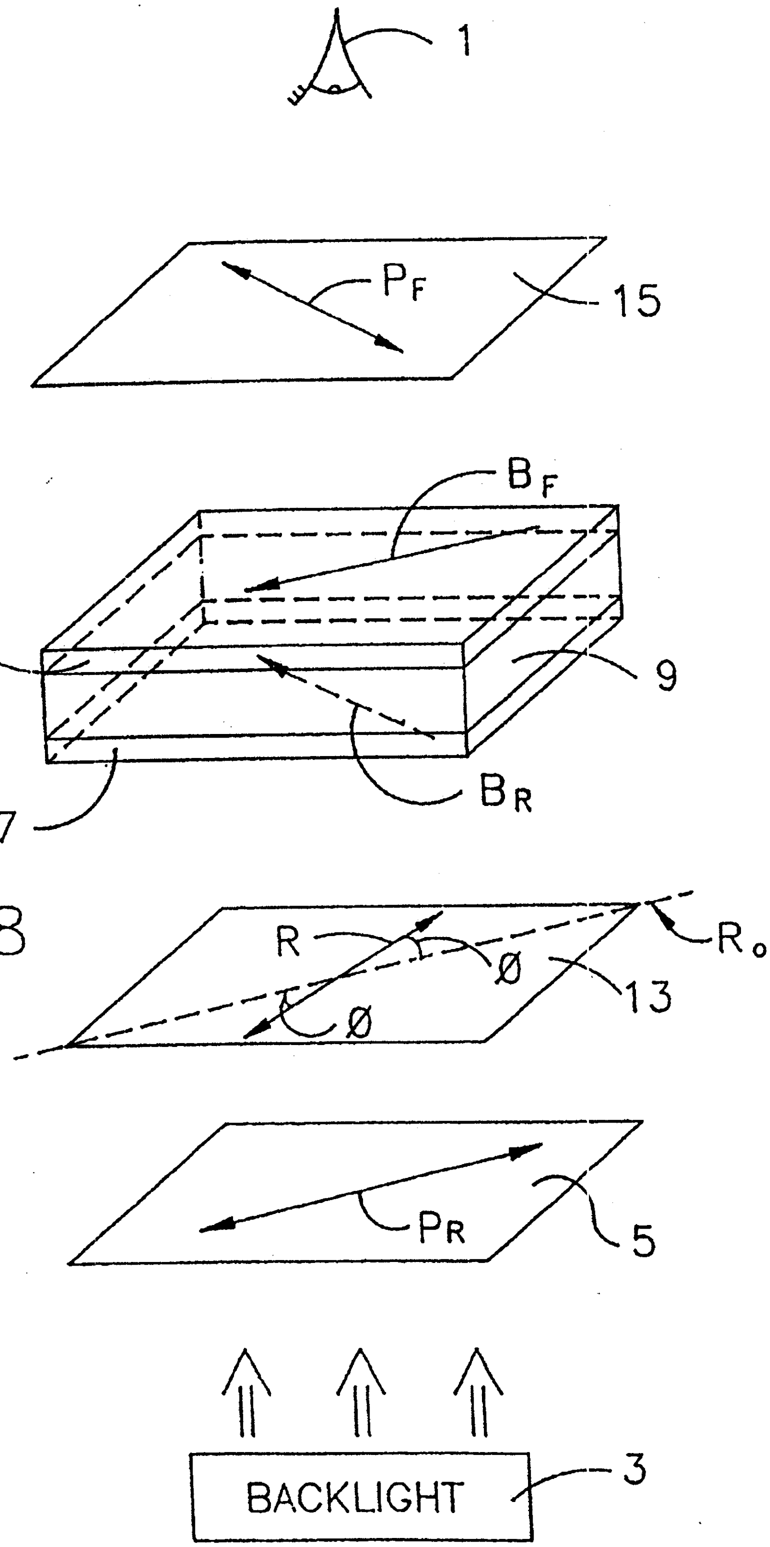


Fig. 8

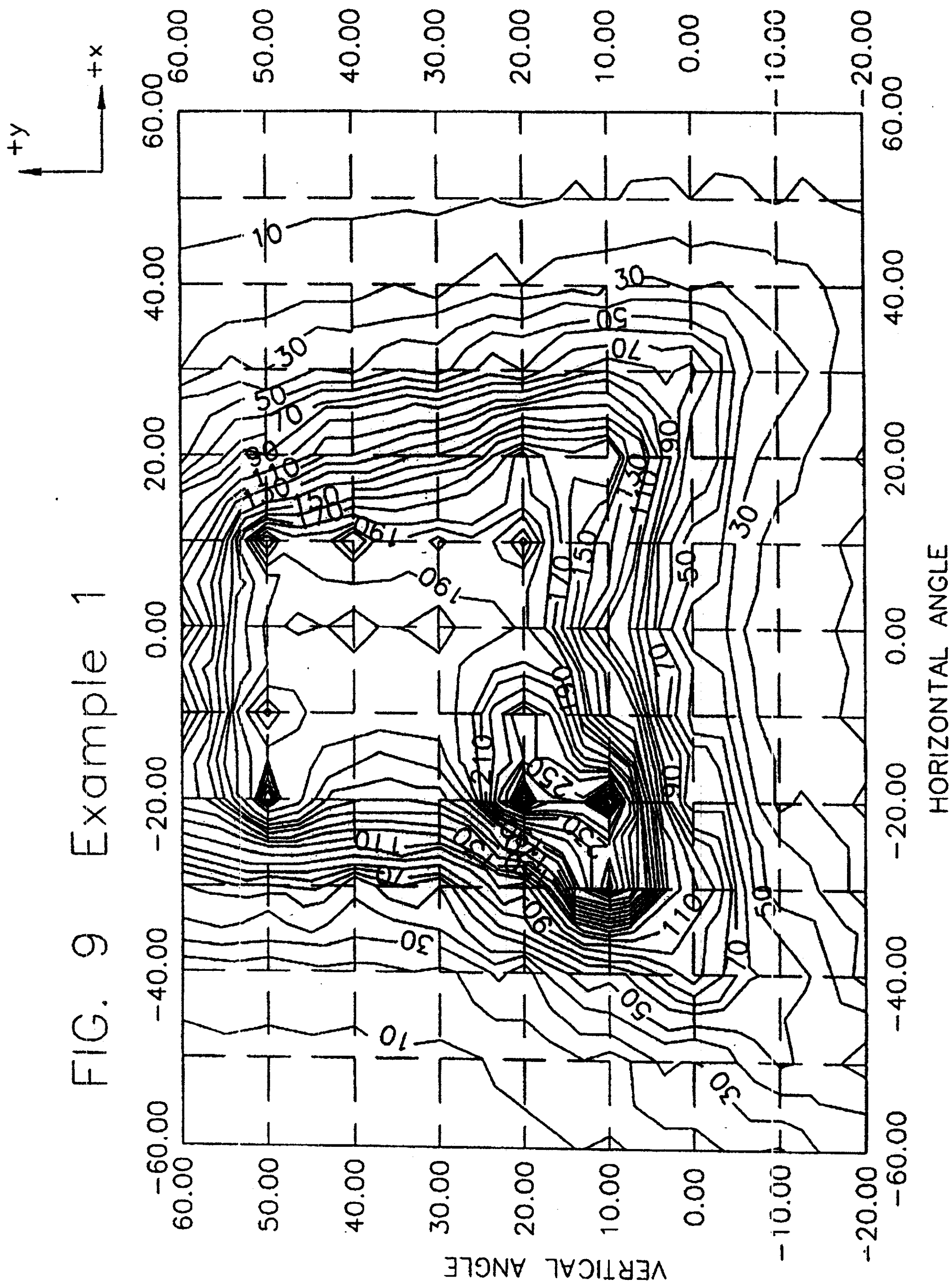


FIG. 9 Example 1

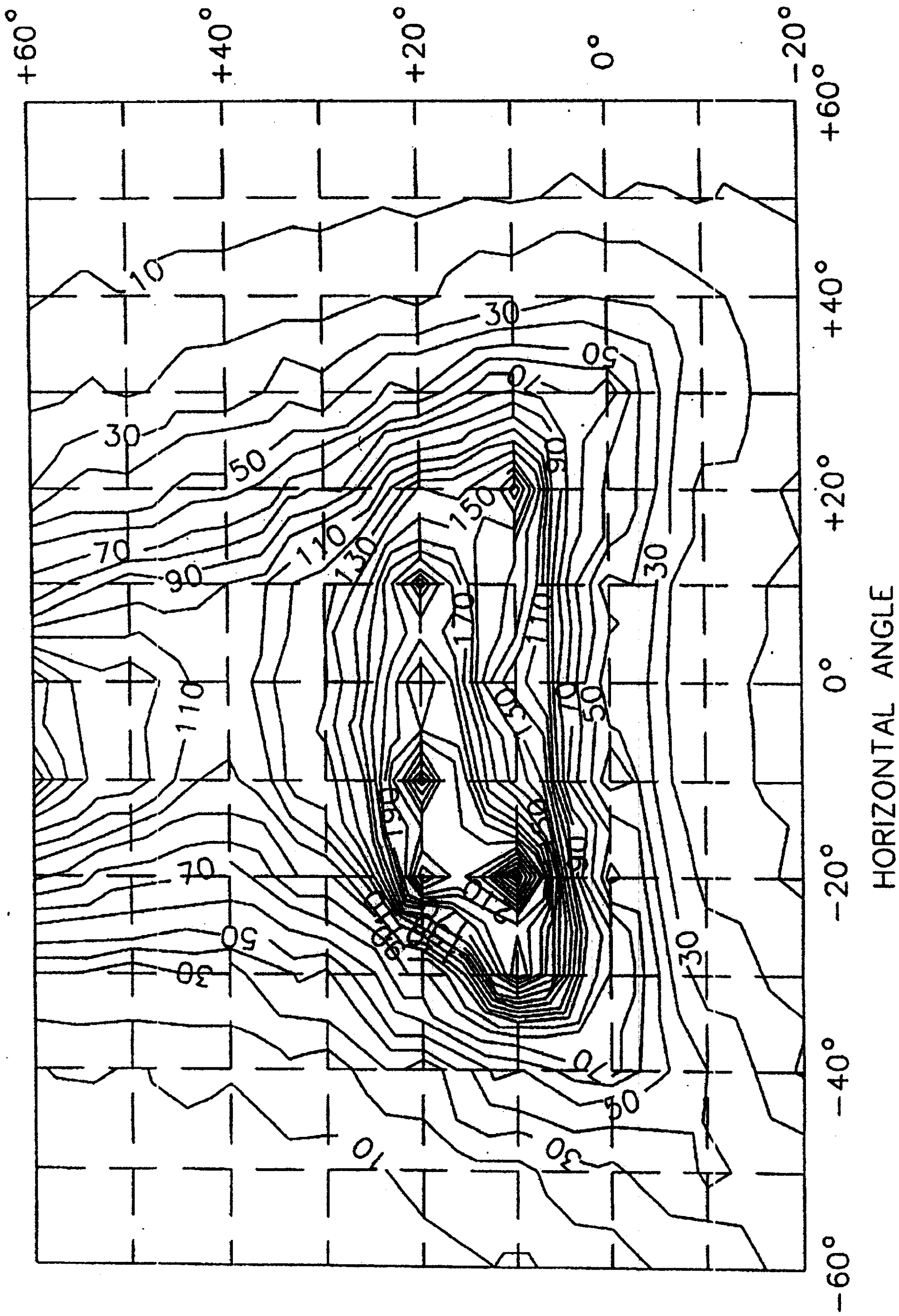


FIG. 10 Example 1

FIG. 11 Example 1

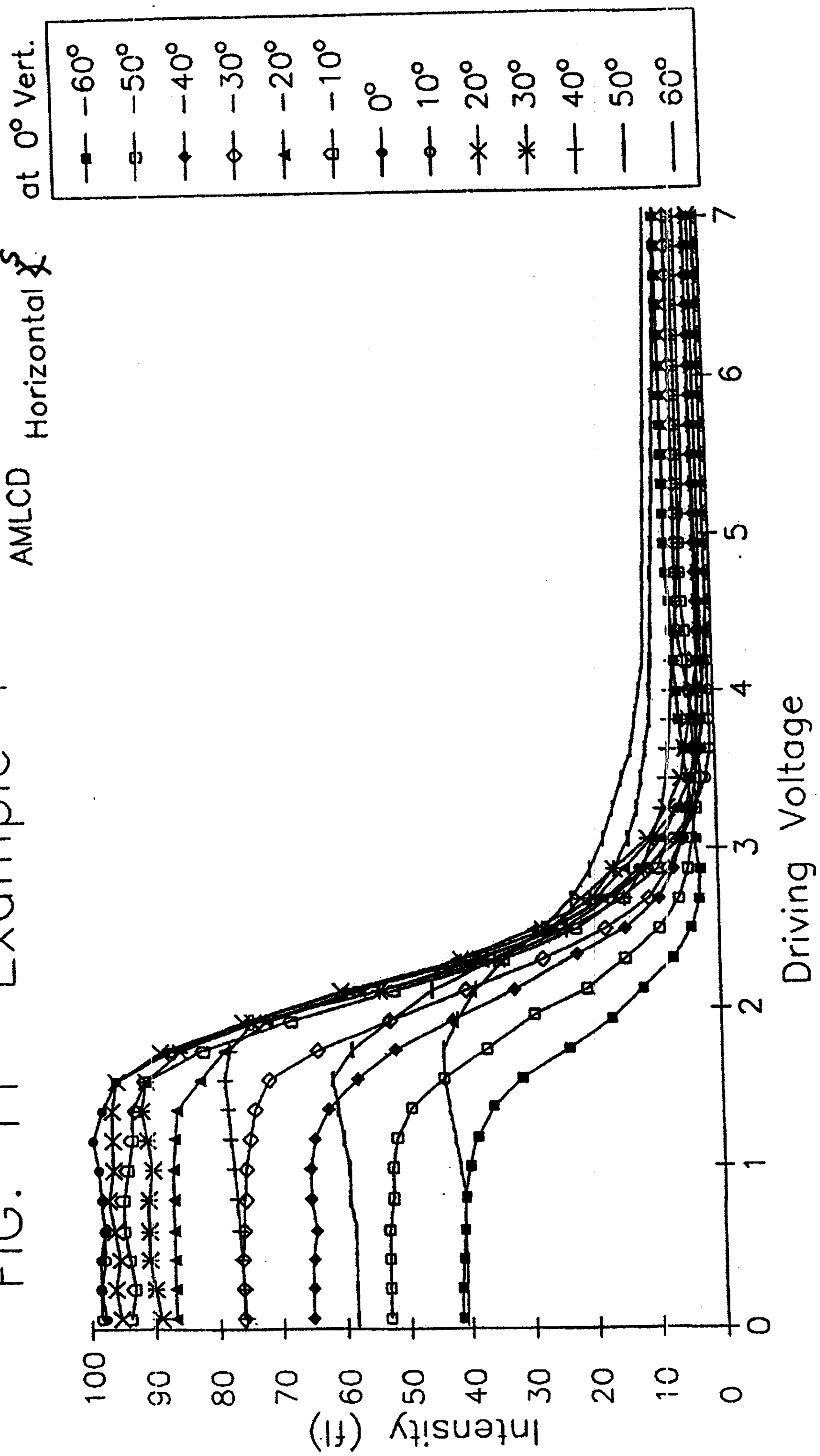


FIG. 12(a) Example 1

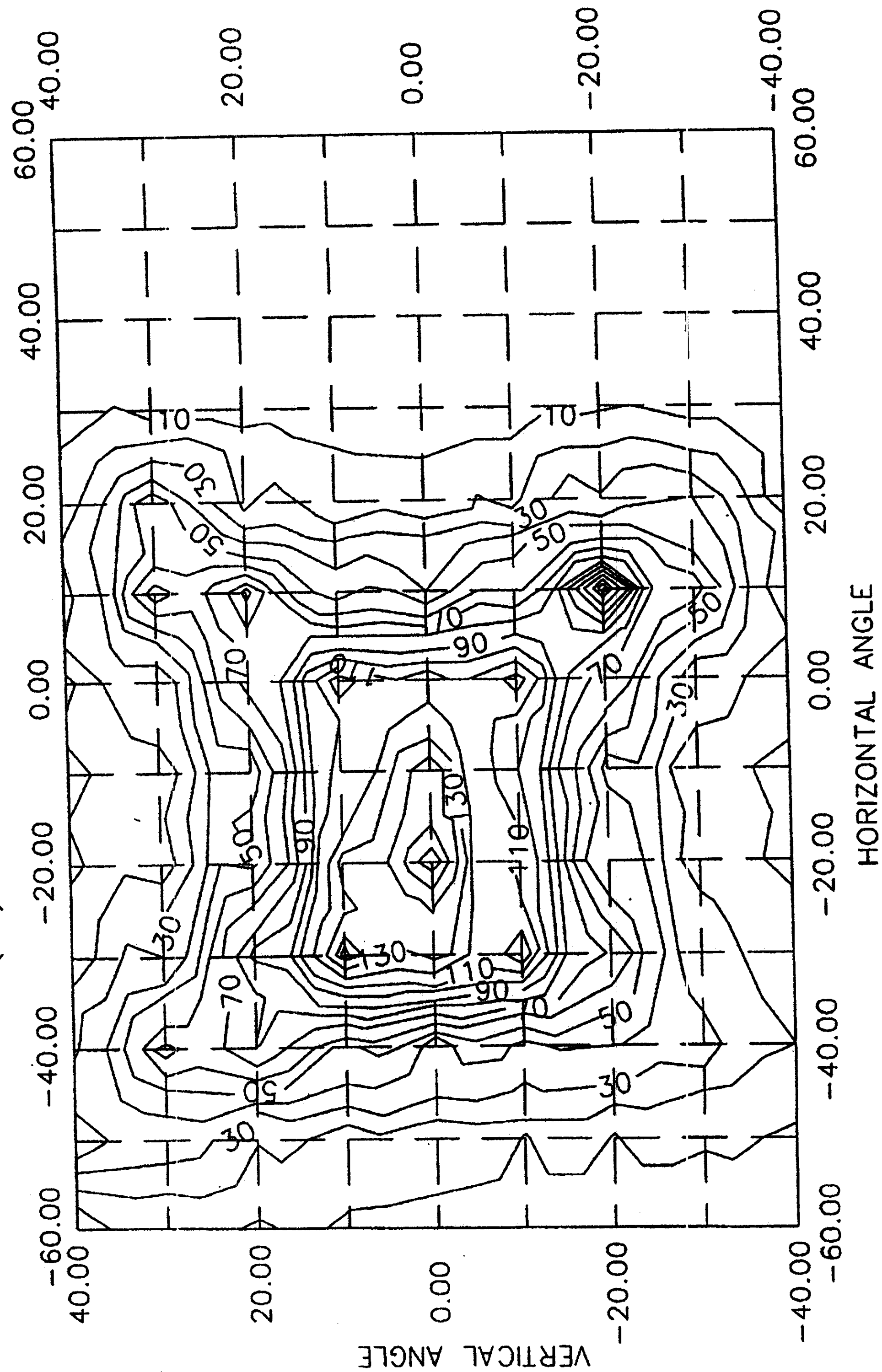


FIG. 12(b) Example 1

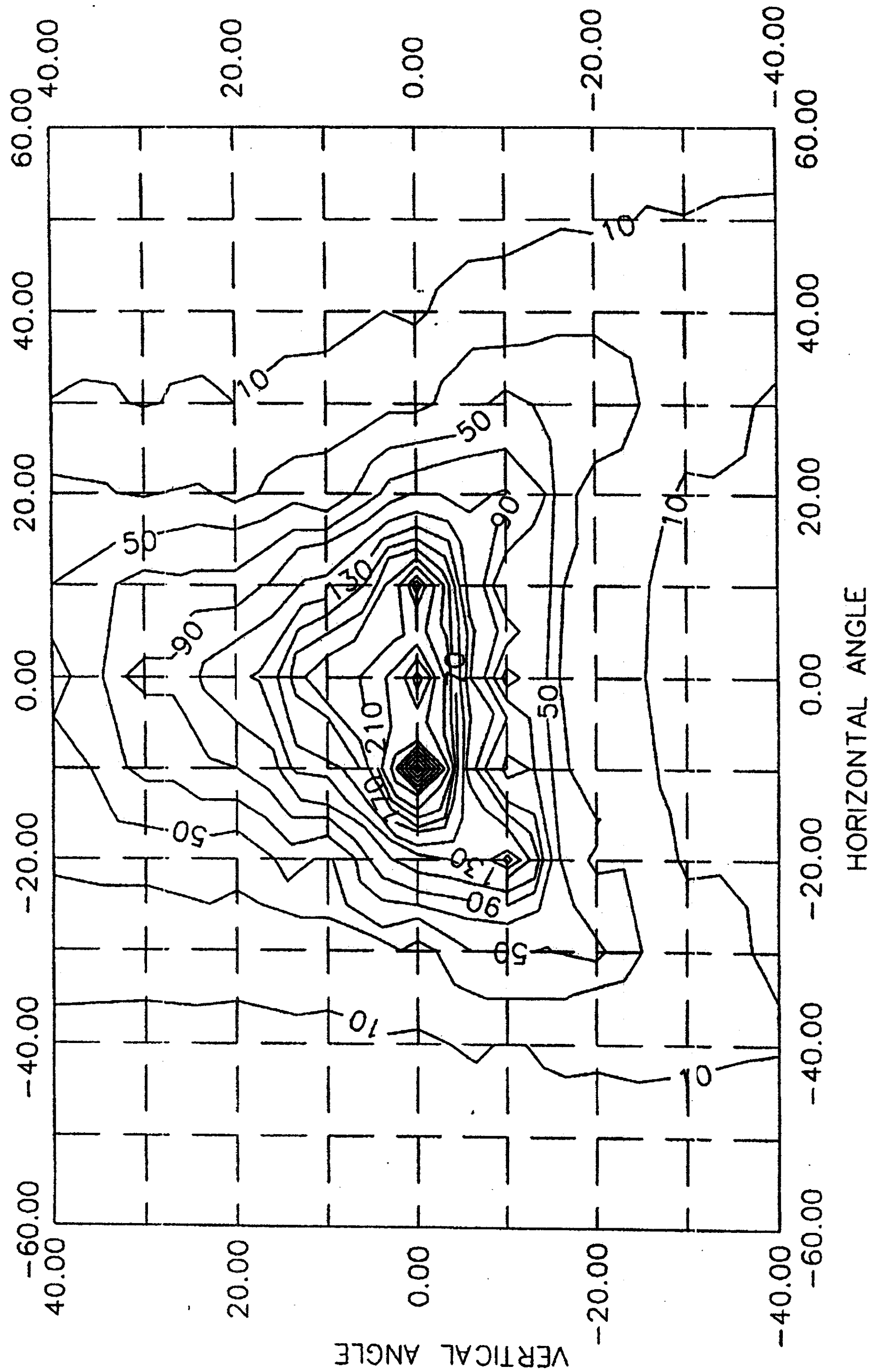


FIG. 13 Example 2

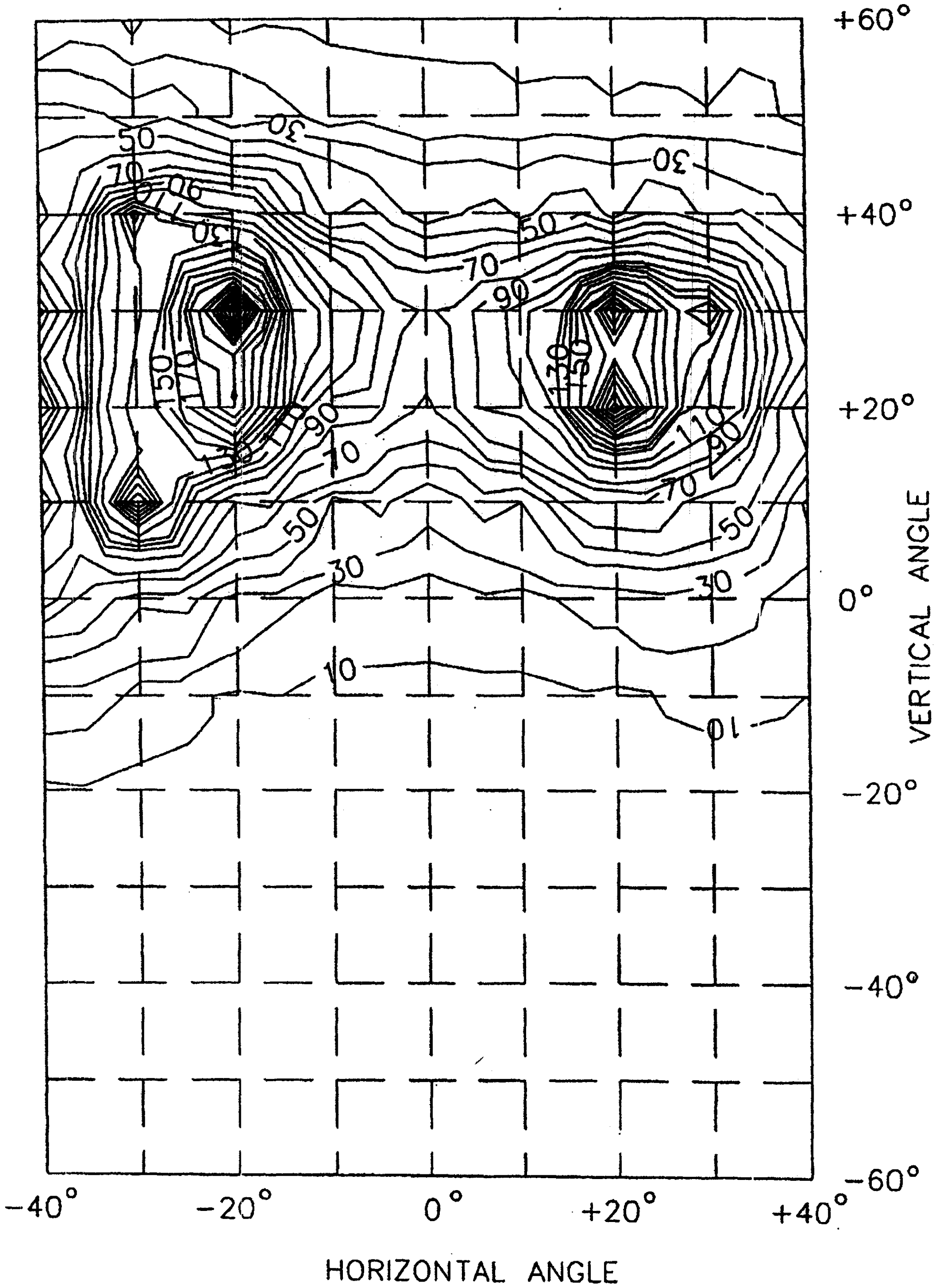


FIG. 14 Example 2

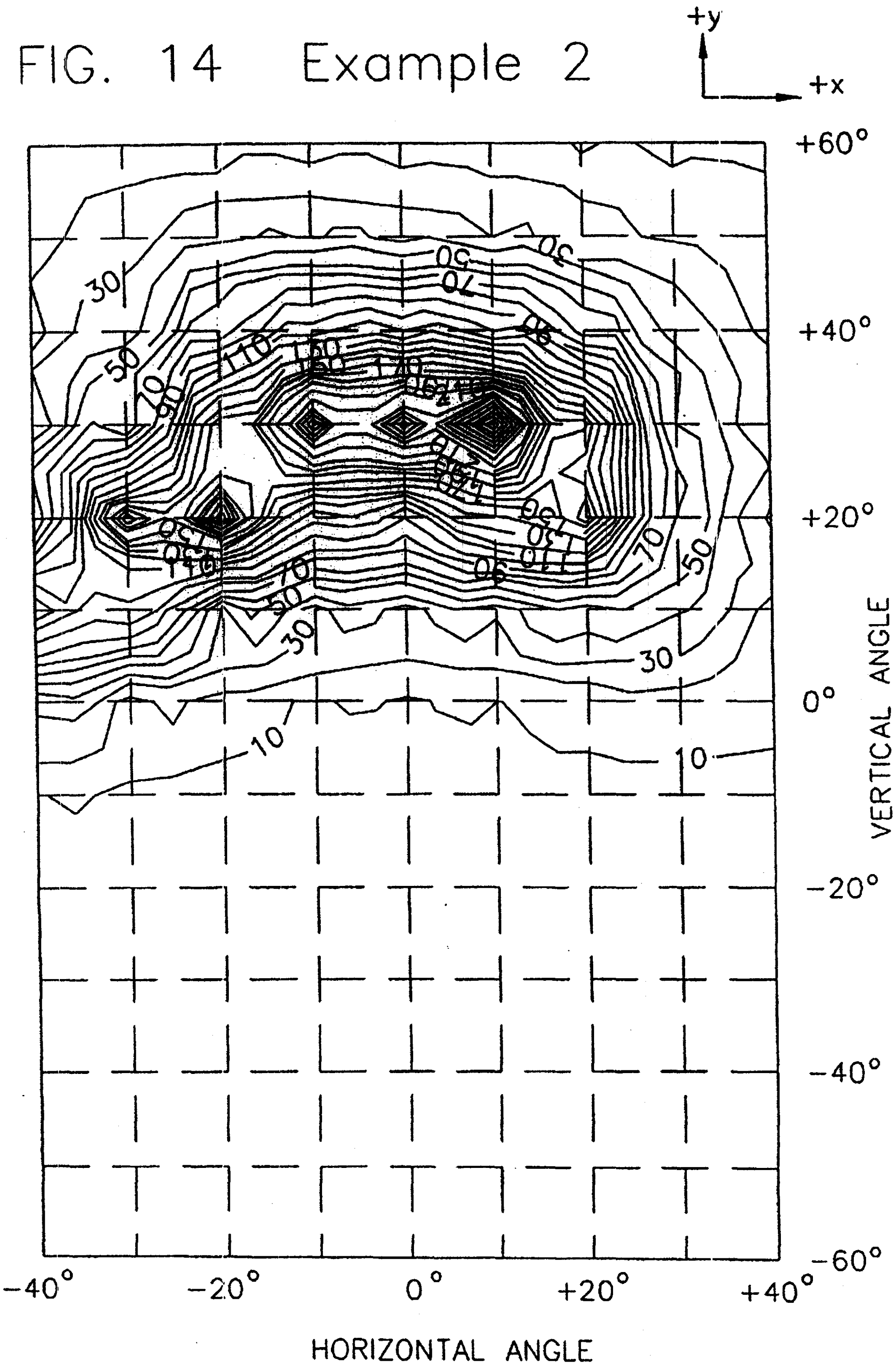


FIG. 15 Example 3

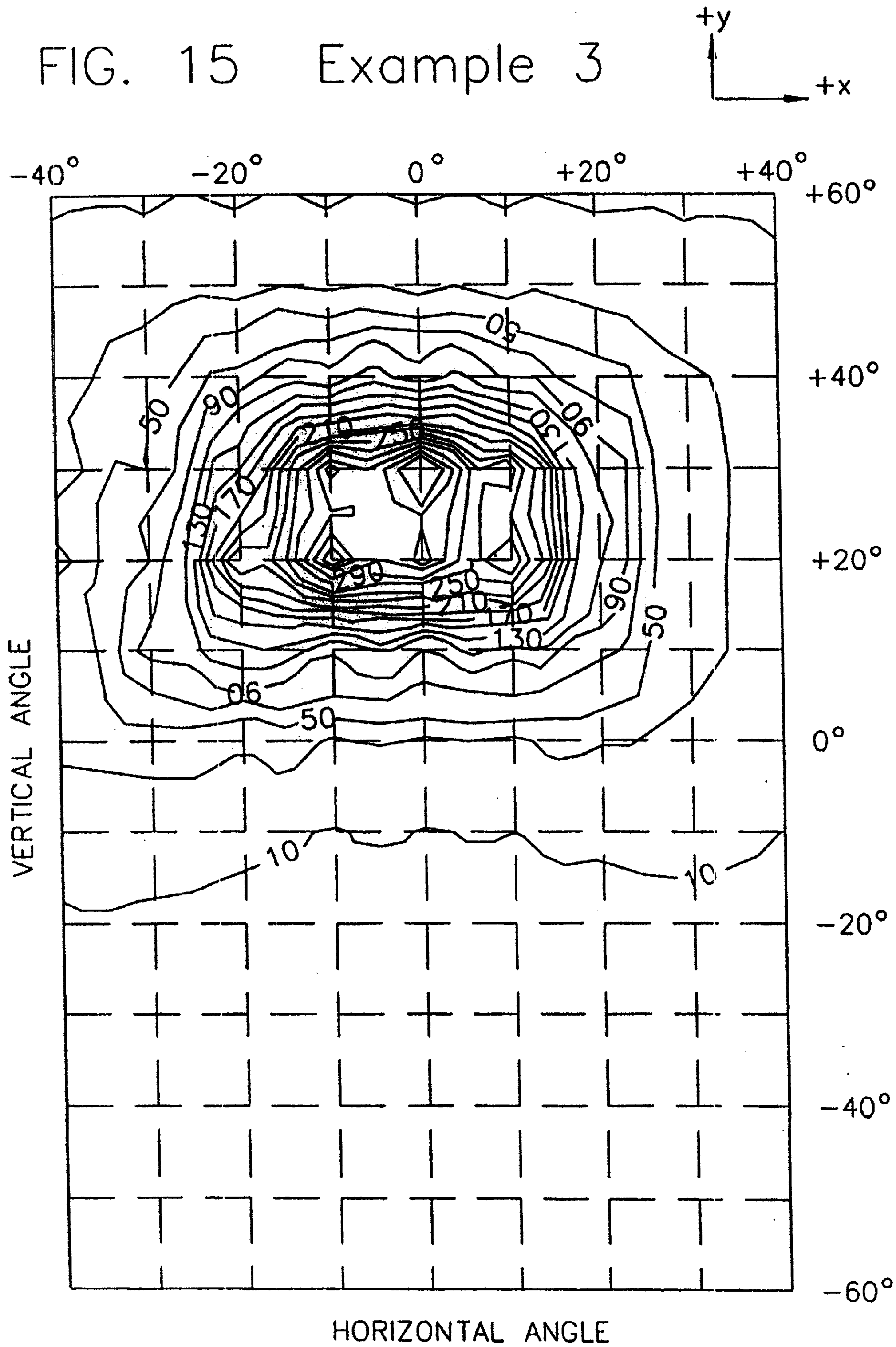
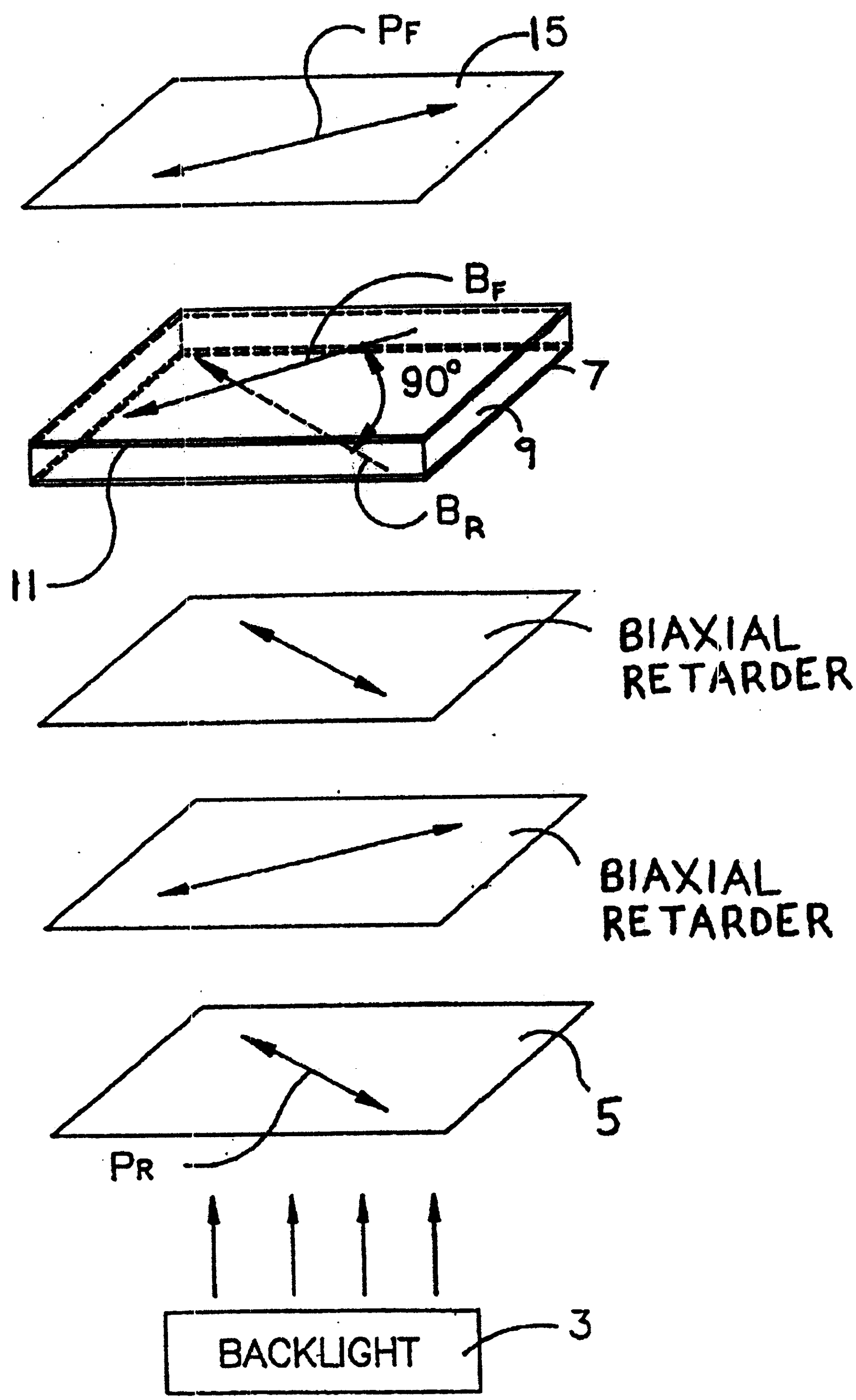


Fig. 16


PF
15
BF
90°
7
9
BR
11
BIAXIAL
RETARDER
BIAXIAL
RETARDER
5
PR
BACKLIGHT
3

NORMALLY WHITE LCD INCLUDING FIRST AND SECOND BIAXIAL RETARDERS

RELATED APPLICATIONS

This is a continuation of U.S. Ser. No. 08/747,671, filed Nov. 12, 1996 (U.S. Pat. No. 5,737,048); which is a continuation of Ser. No. 08/255,971, filed Jun. 8, 1994 (U.S. Pat. No. 5,576,861); which is a CIP of Ser. No. 08/235,691, filed Apr. 29, 1994 (U.S. Pat. No. 5,594,568); and a CIP of Ser. No. 08/167,652, filed Dec. 15, 1993 (U.S. Pat. No. 5,570, 214), the entire disclosures of which are hereby incorporated herein by reference.

This invention relates to a liquid crystal display having at least one retardation film. More particularly, this invention relates to a normally white liquid crystal display including a retardation film disposed on one side of the liquid crystal layer, the optical axis of the retardation film being oriented according to the manufacturer's desired specification.

BACKGROUND OF THE INVENTION

Liquid crystal materials are useful for electronic displays because light traveling through a layer of liquid crystal (LC) material is affected by the anisotropic or birefringent value (Δn) of the LC material which in turn can be controlled by the application of a voltage across the LC. Liquid crystal displays (LCDs) are commonly used in applications such as avionic cockpit displays, portable computers, calculators, etc.

Informational data in typical liquid crystal displays is presented in the form of a matrix array of rows and columns of numerals or characters which are generated by a number of segmented electrodes arranged in a matrix pattern. The segments are connected by individual leads to driving electronics which apply a voltage to the appropriate combination of segments and adjacent LC material in order to display the desired data and/or information by controlling the light transmitted through the liquid crystal material.

Contrast ratio is one of the most important attributes considered in determining the quality of both normally white (NW) and normally black (NB) liquid crystal displays. The contrast ratio in a normally white display is determined in low ambient conditions by dividing the "off-state" light transmission (high intensity white light) by the "on-state" or darkened transmitted intensity. For example, if the "off-state" transmission is 200 fL at a particular viewing angle and the "on-state" transmission is 5 fL at the same viewing angle, then the display's contrast ratio at that particular viewing angle is 40 or 40:1 for the particular "on-state" driving voltage utilized.

Accordingly, in normally white LCDs the primary factor adversely limiting the contrast ratio is the amount of light which leaks through the display in the darkened or "on-state". In a similar manner, in normally black displays, the primary factor limiting the contrast ratio achievable is the amount of light which leaks through the display in the darkened or "off-state". The higher and more uniform the contrast ratio of a particular display over a wide range of viewing angles, the better the LCD.

Normally black (NB) twisted nematic displays typically have better contrast ratio contour curves or characteristics then do their counterpart NW displays in that the NB image can be seen better at large viewing angles. However, NB displays are much harder to manufacture than NW displays due to their high dependence on the cell gap or thickness "d" of the liquid crystal layer as well as on the temperature of the liquid crystal material itself. Accordingly, a long-felt need in the art has been the ability to construct a normally white display with high contrast ratios over a large range of viewing angles, rather than having to resort to the more difficult to manufacture NB display to achieve these characteristics.

What is generally needed in NW displays is an optical compensating or retarding element(s), i.e. retardation film, which introduces a phase delay that restores the original polarization state of the light, thus allowing the light to be substantially blocked by the output polarizer in the "on-state". Optical compensating elements or retarders are known in the art and are disclosed, for example, in U.S. Pat. Nos. 5,184,236, 5,196,953, 5,138,474, and 5,071,997, the disclosures of which are hereby incorporated herein by reference.

FIG. 1 is a contrast ratio curve graph for a prior art normally white twisted nematic light valve including a rear linear polarizer having a transmission axis oriented in a first direction, a front or light exit linear polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another, a liquid crystal material having a cell gap "d" of about 5.86 μm and a birefringence (Δn) of about 0.084 at room temperature, a rear buffing or orientation film buffed in the second direction, and a front orientation film buffed in the first direction. The temperature at which FIG. 1 was developed was about 34.4° C. This light valve did not include a retarder.

The contrast ratio curves of FIG. 1 were plotted utilizing a 6.8 volt "on-state" driving voltage, a 0.2 volt "off-state" or V_{OFF} voltage, and by conventionally backlighting the display with white light. As can be seen in FIG. 1, the viewing zone or envelope of the light valve while being fairly broad horizontally in the lower vertical region becomes narrowed or constricted in, the positive vertical viewing region. For example, at positive 20° vertical, the 10:1 and greater contrast ratio region extends horizontally over only a total of about 70° while at −20° vertical, this same 10:1 contrast ratio zone extends over a horizontal total of about 100°. Therefore, because of the non-uniform or skewed shape of the viewing zone or envelope shown in FIG. 1, it is evident that viewers in the positive vertical viewing region will have difficulty viewing displayed images at medium and large horizontal viewing angles such as about ±40°. This graph is illustrative of the common problems associated with typical normally white liquid crystal displays in that their contrast ratios are limited at increased horizontal and vertical viewing angles.

FIG. 2 is a driving voltage versus intensity (fL) plot of the prior art light valve described above with respect to FIG. 1, this plot illustrating the gray level behavior of this light valve. The various curves represent horizontal viewing angles from about −60° to +60° along the 0° vertical viewing axis.

Gray level performance and the corresponding amount of inversion are important in determining the quality of an LCD. Conventional liquid crystal displays typically utilize anywhere from about 8 to 64 different driving voltages. These different driving voltages are generally referred to as "gray level" voltages. The intensity of light transmitted through the pixel(s) or display depends upon the driving voltage utilized. Accordingly, conventional gray level voltages are used to generate dissimilar shades of color so as to create different colors when, for example, the shades are mixed with one another.

Preferably, the higher the driving voltage in a normally white display, the lower the intensity (fL) of light transmitted therethrough. Likewise then, the lower the driving voltage, the higher the intensity of light reaching the viewer. The opposite is true in normally black displays. Thus, by utilizing multiple gray level driving voltages, one can manipulate either a NW or NB liquid crystal display to emit desired intensities and shades of light/color. A gray level V_{ON} is generally known as any driving voltage greater than V_{th} (threshold voltage) up to about 5–6.5 volts.

Gray level intensity in LCDs is dependent upon the display's driving voltage. It is desireable in NW displays to have an intensity versus driving voltage curve wherein the intensity of light emitted from the display or pixel continually and monotonically decreases as the driving voltage increases. In other words, it is desireable to have gray level performance in an NW pixel such that the intensity (fL) at 6.0 volts is less than that at 5.0 volts, which is in turn less than that at 4.0 volts, which is less than that at 3.0 volts, which is in turn less than that at 2.0 volts, etc. Such desired gray level curves across wide ranges of view allow the intensity of light reaching viewers at different viewing angles via the pixel(s) or display to be easily and consistently controlled.

Turning again to FIG. 2, the intensity versus driving voltage curves illustrated therein of the FIG. 1 light valve having no retardation film are undesireable because of the inversion humps present in the areas of the curves having driving voltages greater than about 3 or 3.2 volts. The intensity aspect of the curves monotonically decreases as the driving voltage increases in the range of from about 1.6–3.0 volts, but at a driving voltage of about 3.2 volts, the intensities at a plurality of viewing angles begin to rise as the voltage increases from about 3.2 volts up to about 6.8 volts. Such rises in intensity as the driving voltage increases are known as "inversion humps". Inversion humps lead to the display or light valve emitting different colors via the same pixel at different viewing angles for the same driving voltage. Clearly, this is undesirable. Whilte the inversion humps of FIG. 2 include only rise portions, inversion humps often include both rise and fall portions as will be appreciated by those of ordinary skill in the art, thus enabling the "inversion humps" to actually look like humps.

A theoretically perfect driving voltage versus intensity (fL) curve for an NW display would have a decreased intensity (fL) for each increase in gray level driving voltage at all viewing angles. In contrast to this, the inversion humps of FIG. 2 represent large increases in intensity of radiation emitted from the light valve for each corresponding increase in gray level driving voltage above about 3.2 volts. Accordingly, it would satisfy a long-felt need in the art if a normally white liquid crystal display could be provided with no or little inversion.

U.S. Pat. No. 5,184,236 discloses an NW display including a pair of retardation films provided on one side of the LC layer, these retardation films having retardation values of about 300 nm or greater. The viewing characteristics of the LCDs of this patent could be improved upon with respect to contrast ratio, inversion, and uniformity as well as the position of the viewing zone by utilizing retarders of different values and orientations. Furthermore, it is felt that such improvements may be achieved with a reduced number of retardation films thus reducing the cost and complexity of the display.

The parents of this application, i.e. Ser. Nos. 08/167,652 and 08/235,691 incorporated herein by reference, provide for NW displays with a pair of retardation films having retardation values of about 80–200 nm. While the different embodiments of Ser. No. 08/167,652 and 08/235,691 provide excellent results with respect to viewing characteristics, the disclosure of this application allows improved viewing characteristics in the vertical viewing regions while sacrificing certain viewing characteristics at other viewing angles.

FIG. 3 illustrates the angular relationships between the horizontal and vertical viewing axes and angles described herein relative to a liquid crystal display and conventional LCD angles ϕ and Θ. The +X, +Y, and +Z axes shown in FIG. 3 are also defined in other figures herein. Furthermore, the "horizontal viewing angles" (or X_{ANG}) and "vertical viewing angles" (or Y_{ANG}) illustrated and described herein may be transformed to conventional LCD angles: azimuthal angle ϕ; and polar angle Θ, by the following equations:

$$\mathrm{Tan}(X_{ANG})=\mathrm{Cosine}(\phi)\cdot\mathrm{Tan}(\Theta)$$

$$\mathrm{Sine}(Y_{ANG})=\mathrm{Sine}(\Theta)\cdot\mathrm{Sine}(\phi)$$

or

$$\mathrm{Cosine}(\Theta)=\mathrm{Cosine}(Y_{ANG})\cdot\mathrm{Cosine}(X_{ANG})$$

$$\mathrm{Tan}(\phi)=\mathrm{Tan}(Y_{ANG})\div\mathrm{Sine}(X_{ANG})$$

The term "rear" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones, and orientation films means that the described element is on the backlight side of the liquid crystal material, or in other words, on the side of the LC material opposite the viewer.

The term "front" when used herein but only as it is used to describe substrates, polarizers, electrodes, buffing zones and orientation films means that the described element is located on the viewer side of the liquid crystal material.

The LCDs and light valves herein include a liquid crystal material with a birefringence (Δn) of 0.084 at room temperature, Model No. ZLI-4718 obtained from Merck.

The term "retardation value" as used herein means "$d\cdot\Delta n$" of the retardation film or plate, wherein "d" is the film thickness and "Δn" is the film birefringence.

The term "interior" when used herein to describe a surface or side of elements (or an element itself), means the side or surface closest to the liquid crystal material.

The term "light valve" as used herein means a liquid crystal display including a rear linear polarizer, a rear transparent substrate, a rear continuous pixel electrode, a rear orientation film, an LC layer, a front orientation film, a front continuous pixel electrode, a front substrate, and a front polarizer (without the presence of color filters and driving active matrix circuitry such as TFTs). Such a light valve may also include a retardation film(s) disposed on either side of the LC layer as described with respect to each example and embodiment herein. In other words, a "light valve" may be referred to as one giant pixel without segmented electrodes.

It is apparent from the above that there exists a need in the art for a normally white liquid crystal display wherein the viewing zone of the display has both high contrast ratios and little or no inversion over a wide range of viewing angles, the viewing zones position being shiftable to different vertical regions so as to allow viewers at such predetermined viewing angles (e.g. positive vertical viewing angles) to be able to satisfactorily view the displayed image.

This invention will now be described with respect to certain embodiments thereof, accompanied by certain illustrations wherein:

SUMMARY OF THE INVENTION

Generally speaking this invention fulfills the above-described needs in the art by providing a method of shifting the high contrast ratio viewing zone of a twisted nematic normally white liquid crystal display upward into the positive or upward vertical viewing zone, the method comprising the steps of:

a) sandwiching a twisted nematic liquid crystal layer between a pair of electrodes, the liquid crystal layer having a thickness of from about 4.5–6.5 μm;

b) orienting the liquid crystal molecules on a first side of the liquid crystal layer in a first direction;

c) orienting the liquid crystal molecules on a second side of the liquid crystal layer in a second direction, the first and second directions being different from one another in a manner such that the liquid crystal layer when in the off-state twists at least one visible wavelength of light less than about 100°;

d) providing a retardation film having a retardation value "d·Δn" in the range of about 100–250 nm on the first side of the liquid crystal layer, wherein "d" is the thickness of the retardation film and "Δn" is its birefringence;

e) rotating the optical axis of the retardation film from above 2°–20° relative to the second direction, the rotating of the optical axis shifting the high contrast viewing zone vertically so that viewers at such viewing angles may see a high contrast image with reduced inversion.

This invention further fulfills the above-described needs in the art by providing a twisted nematic liquid crystal display capable of displaying an image to a viewer, the display comprising:

a pair of electrodes sandwiching a twisted nematic liquid crystal layer therebetween, the pair of electrodes for applying a voltage across the liquid crystal layer;

first and second orientation means disposed adjacent the liquid crystal layer on opposite sides thereof, the first orientation means defining a first orientation or buffing direction and the second orientation means defining a second orientation or buffing direction, the first and second orientation directions for aligning the liquid crystal molecules of the liquid crystal layer in a predetermined manner;

a positively birefringent unaxial retardation film having a retardation value "d·Δn" in the range of about 100–200 nm, where "d" is the thickness of the retardation film and "Δn" is its birefringent value, wherein the retardation film is disposed on the same side of the liquid crystal layer as the first orientation means, the retardation film being oriented such that its optical axis is substantially parallel ±about 20° to the second orientation or buffing direction of the second orientation means thereby enabling the liquid crystal display to display to the viewer an image with improved contrast ratios and reduced inversion.

This invention further fulfills the above-described needs in the art by providing a method of making a normally white twisted nematic liquid crystal display, a method comprising the steps of:

a) sandwiching a liquid crystal layer between first and second electrodes, the liquid crystal layer having a thickness "d" of from about 4.5 to 6.5 μm;

b) providing a first orientation means between the first electrode and the liquid crystal layer, the first orientation means for orienting LC molecules of the LC layer in a first direction adjacent the first orientation means;

c) providing a second orientation means between the LC layer and the second electrode, the second orientation means for orienting LC molecules in a second direction adjacent the second orientation means;

d) disposing a positively birefringent uniaxial retardation film on the same side of the LC layer as the first electrode and first orientation means, the retardation film having a retardation value of from about 100–200 nm; and

e) orientating the optical axis of the uniaxial retardation film substantially parallel ± about 20° to the second direction defined by the second orientation means whereby the normally white display exhibits improved contrast ratios and reduced inversion.

This invention will now be described with respect to certain embodiments thereof, wherein:

IN THE DRAWINGS

FIG. 1 is a contrast ratio plot of a prior art light valve which utilized white light and an "on-state" driving voltage of about 6.8 volts.

FIG. 2 is an intensity versus driving voltage plot of the prior art light valve of FIG. 1, this plot illustrating a fairly large amount of undesireable inversion over a wide range of horizontal viewing angles at driving voltages greater than about 3 volts.

FIG. 3 is a graph illustrating the angular relationship between the horizontal and vertical viewing angles discussed herein, and their relationship with conventional liquid crystal display viewing angles: azimuthal angle ϕ; and polar angle Θ.

FIG. 4 is an exploded perspective schematical diagram of the optical components and their respective orientations of an LCD according to a first embodiment of this invention.

FIG. 5 is a top view illustrating the optical component angular relationships of the liquid crystal display of FIG. 4.

FIG. 6 is a side elevational cross-sectional view of the LCD of the first or FIGS. 4–5 embodiment of this invention.

FIG. 7 is an exploded perspective schematical diagram of the optical components and their respective orientations of an LCD according to a second embodiment of this invention, this embodiment being "P-buffed" as opposed to the "X-buffed" first embodiment.

FIG. 8 is an exploded perspective schematical diagram of the optical components and their respective orientations of an LCD according to a third embodiment of this invention wherein the retardation film is disposed on the rear or backlight side of the liquid crystal layer.

FIG. 9 is a white light contrast ratio contour plot of the normally white Display "A" of Example 1 when a driving voltage of about 6.8 volts was applied.

FIG. 10 is a white light contrast ratio contour plot of the normally white Display "A" of Example 1 when utilizing a driving voltage of about 6.0 volts was applied.

FIG. 11 is a white light transmission (fL) versus driving voltage plot of the normally white Display "A" of Example 1, this plot illustrating the viewing characteristics at a plurality of horizontal viewing angles disposed along the 0° vertical viewing axis.

FIG. 12(*a*) is a white light contrast ratio contour plot of the comparative normally white Display "B" of Example 1 when a driving voltage of about 6.8 volts was applied.

FIG. 12(*b*) is a white light contrast ratio contour plot of the comparative NW Display "C" of Example 1 when a driving voltage of about 6 volts was applied.

FIG. 13 is a white light contrast ratio contour plot of the NW light valve of Example 2 when a driving voltage of about 5.0 volts was applied.

FIG. 14 is a white light contrast ratio contour plot of the NW light valve of Example 2 when a driving voltage of about 4.0 volts was applied.

FIG. 15 is a white light contrast ratio contour plot of the normally white AMLCD of Example 3 when a driving voltage of about 6.0 volts was applied.

FIG. 16 is an exploded perspective schematical view of the optical components and their respective orientations of another embodiment of this invention wherein first and second retardation films (uniaxial or biaxial) are disposed on one side of the liquid crystal layer, as disclosed in U.S. Pat. No. 5,594,568 (Ser. No. 235,691), which was incorporated herein by reference above.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS OF THIS INVENTION

Referring now more particularly to the accompanying drawings in which like reference numerals indicate like parts.

FIG. 4 is an exploded schematic view of the optical components and their respective orientations of an LCD according to a first embodiment of this invention, the LCD being an AMLCD having a matrix array of pixels and colored subpixels in certain embodiments. As shown, this display (or display assembly) includes from the rear forward toward viewer 1, conventional backlight 3, rear or light-entrance linear polarizer 5, rear buffing or orientation film 7, liquid crystal layer 9, front buffing or orientation film 11, retardation film 13, and finally front or light-exit linear polarizer 15.

Backlight 3 is conventional in nature and emits substantially collimated or alternatively diffused light toward the display panel including rear polarizer 5 in certain embodiments of this invention. Backlight 3 may be, for example, the backlighting assembly disclosed in commonly owned U.S. Pat. No. 5,161,041, the disclosure of which is hereby incorporated herein by reference. Other conventional high intensity substantially collimated backlight assemblies may also be used.

Rear and front polarizers 5 and 15 are linear in nature in certain embodiments of this invention and their respective linear transmission axes P_R and P_F are orientated such that the displays of the different embodiments are of the normally white (NW) type. Therefore, when a driving voltage below the threshold voltage V_{th} is applied across liquid crystal layer 9, transmission axes P_R and P_F of polarizers 5 and 15 respectively are orientated such that the light emitted from backlight 3 proceeds through and is linearly polarized in direction P_R by polarizer 5, is then twisted (e.g. about 80°–100°) by LC material 9, and finally exits polarizer 15 via transmission axis P_F thus reaching viewer 1. The light reaches viewer 1 because its polarization directon upon reaching front polarizer 15 is similar to that of axis P_F. Thus, a NW display or pixel to which a voltage less than V_{th} is applied is said to be in the "off-state" and appears white (or colored if colored filters are present) to the viewer.

However, when a substantial driving voltage (e.g. about 6 volts) is applied across selected NW pixels of the matrix array including liquid crystal layer 9, the light transmitted through rear polarizer 5 is not significantly twisted by LC layer 9 and thus is substantially blocked by front polarizer 15 due to the fact that the polarization direction of light reaching the interior surface of front polarizer 15 is substantially perpendicular to transmission axis P_F thereby resulting in substantially no light reaching viewer 1 by way of the selected pixels to which the substantial driving voltage is applied. Thus, the selected pixels driven in the matrix array appear darkened to viewer 1, these pixels said to be in the "on-state". As will be appreciated by those of skill in the art, the amount of light reaching viewer 1 is dictated by the voltage applied to LC layer 9—the higher the driving voltage, the darker the selected driven pixel(s) appear.

In certain embodiments of this invention, transmission axis P_R of rear polarizer 5 and transmission axis P_F of front polarizer 15 are oriented in a manner substantially perpendicular to one another so as to define a normally white twisted nematic cell. However, polarizers 5 and 15 may be oriented in other conventional manners which also allow the cell or display to be of the normally white type.

Rear and front orientation or buffing films 7 and 11, respectively, are conventional and made of a substantially transparent polyimide in certain embodiments of this invention. Rear orientation film 7 is conventionally buffed or oriented in direction B_R as shown in FIG. 4. Likewise, front film 11 is conventionally buffed in direction B_F. Buffing directions B_R and B_F are oriented substantially perpendicular to one another in certain embodiments of this invention so as to allow the molecules of liquid crystal layer 9 when in the off or non-driven state to be twisted from about 80°–100°, most preferably about 90°. The term "off-state" means that a voltage below the threshold voltage (V_{th}) is applied across LC layer 9.

Due to the orientation of buffing directions B_R and B_F of orientation films 7 and 11 respectively, the polarization direction of normally incident light emitted from backlight 3 reaching liquid crystal material 9 is twisted in a conventional manner by the liquid crystal molecules as it passes through layer 9, when, of course, the display (or selected pixels thereof) is in the off-state.

However, when a substantially full driving voltage, e.g. about 6 volts or above, is applied to liquid crystal layer 9 (or selected pixels thereof to form the intended image), the normally incident light from backlight 3 reaching layer 9 is permitted to pass therethrough while substantially maintaining its initial direction of polarization. This is due to the fact that when a voltage is applied across LC material 9, the LC molecules are caused to become substantially aligned with one another in the vertical direction as shown in FIG. 4. Therefore, little or substantially no twisting occurs when such a driving voltage (e.g. about 6 volts) is applied and thus the direction of polarization of light passing through layer 9 is substantially maintained.

The voltage amount applied across LC layer 9 determines the degree of twisting of the liquid crystal molecules and thus dictates the polarization direction of light emitted from the front or viewer side of layer 9. In turn, the polarization direction of light reaching polarizer 15 dictates the amount of light permitted to pass therethrough via axis P_F and reach viewer 1 in that the closer aligned transmission axis P_F and the polarization direction of light reaching polarizer 15, the more light which is allowed to pass and reach viewer 1.

While the application of voltage>V_{th} to layer 9 causes the LC molecule to substantially align vertically, the LC molecules never completely stand on end or become perfectly aligned in the vertical direction as is known in the art. This gives rise to the need for retardation film(s).

Retardation film 13 in this first embodiment is disposed on the viewer side of liquid crystal layer 9 thereby being

sandwiched between front polarizer 15 and front orientation film 11. Surprisingly, it has been found that the provision of retardation film 13 on a single side of twisted nematic LC layer 9 reduces inversion and improves viewing zone contrast ratios at large viewing angles when the retardation value of the film is reduced relative to the prior art to retardation values of from about 100–200 mm.

Retardation film 13 in certain embodiments of this invention is positively birefringent and uniaxial in nature, this film being obtained from, for example, Nitto Corporation, Japan, or Nitto Denko America, Incorporated, New Brunswick, N.J. as Model No. NRF-140 (140 nm retarder).

Alternatively, it is believed that biaxial retardation films having similar retardation values may also provide excellent results, such biaxial retardation films and values being disclosed in aforementioned U.S. Ser. No. 08/235,691 filed Apr. 29, 1994.

With reference to FIGS. 4–5, axis P_R and direction B_F are substantially parallel to one another in certain embodiments of this invention while direction B_R, axis P_F, and direction R (or R_0) are also substantially parallel ±about 5° to one another. Accordingly, in such embodiments, axis P_R and direction B_R are substantially perpendicular to one another as are axis P_F and direction B_F. A display having such an optical arrangement is said to be "X-buffed". The term "X-buffed" means that rear polarizer axis P_R is substantially perpendicular to rear buffing direction B_R while front polarizer axis P_F is substantially perpendicular to front buffing direction B_F. Thus, the first embodiment of this invention illustrated in FIGS. 4–6 is an LCD of the "X-buffed" type.

Alternatively, an LCD may be "P-buffed" instead of "X-buffed" in certain embodiments, "P-buffed" meaning that rear polarizer axis P_R is substantially parallel to rear buffing direction B_R and front polarizer axis P_F is substantially parallel to front buffing direction B_F.

Optical axis R of retardation film 13 in the first embodiment of this invention (see FIGS. 4–6) may be aligned in direction R_0 so as to be substantially parallel to axis P_F and buffing direction B_R. Alternatively, optical axis R of retardation film 13 may be rotated either clockwise or counterclockwise relative to directions R_0 and B_R.

The effect of rotating optical axis R of film 13 relative to direction R_0 is to shift the viewing zone or envelope of the display vertically into either the upper or lower vertical region as will be further discussed in the examples below. When film 13 is disposed forward of LC layer 9 and optical axis R of retardation film 13 is rotated clockwise relative to direction R_0 (as shown in FIGS. 4–5) so as to define angle Θ therebetween, the high contrast viewing envelope of the display is shifted into the upper or positive vertical region so as to provide viewer 1 with a high contrast ratio image at increased positive vertical viewing angles. To achieve such a high quality shifted image in the positive vertical region, optical axis R of retardation film 13 is rotated clockwise (to define Θ) from about 2°–20° relative to R_0, more preferably about 4°–15°, and most preferably from about 6°–10° in certain embodiments of this invention. The term "clockwise" is defined as being viewed from the position of viewer 1 in FIG. 4 (or as shown in FIGS. 4–5).

Alternatively, optical axis R of film 13 may be rotated counterclockwise relative to direction R_0 so as to shift the high contrast viewing envelope of the display into the negative vertical viewing region when film 13 is positioned forward of LC layer 9. The same degrees of rotation discussed above relative to clockwise rotation of axis R also apply to this alternative counterclockwise rotation of optical axis R relative to directions R_0 and B_R.

The ability to shift the viewing zone vertically via rotation of film 13 is advantageous in that it allows for excellent positive or negative vertical viewing charactertistics in situations where they are needed. Thus, if a customer desires good positive vertical viewing, the manufacturer need simply rotate optical axis R of retardation film 13 in the clockwise direction as discussed above.

The retardation value "d·Δn" of retardation film 13 is a critical parameter in achieving the surprising results of the different embodiments of this invention, where "d" is the thickness of the retardation film and "Δn" is its birefringent value. In certain embodiments, retardation film 13 is of the uniaxial positively birefringent type and has a retardation value of from about 100–200 nm, more preferably from about 110–180 nm, and most preferably from about 120–160 nm. The biaxial retardation values of the biaxial retarders disclosed in Ser. No. 08/235,691 will also suffice in certain embodiments. In certain embodiments of this invention, as disclosed in U.S. Pat. No. 5,594,568 (i.e. Ser. No. 08/235, 691) which was incorporated into this application by reference on page 1 of this application, first and second biaxial negative retarders, each having a retardation value $d \cdot \Delta n_{xy}$ of from about −10 to −100 nm, may be provided for improving the viewing characteristics of the display. In certain embodiments, the first and second negative biaxial retardation films or layers may be provided on the same side of the liquid crystal layer.

FIG. 6 is a side elevational cross-sectional view of the NW liquid crystal display of the first embodiment of this invention. As shown, the display includes the optical elements illustrated in FIGS. 4–5 as well as rear transparent substrate 17, front transparent substrate 19, rear electrode 21, and front electrode 23.

Transparent substrates 17 and 19 are made of glass or transparent plastic in certain embodiments of this invention, rear substrate 17 being sandwiched between rear polarizer 5 and rear electrode 21 and front transparent substrate 19 being disposed between front electrode 23 and retardation film 13. Alternatively, retardation film 13 may be disposed interior substrate 19 as opposed to its exterior position shown in FIG. 6.

Rear and front electrodes 21 and 23 are conventional in nature and made of transparent ITO in certain embodiments of this invention. While electrodes 21 and 23 are both shown in FIG. 6 as being continuous in nature, rear electrode 21 in AMLCD applications may be conventionally segmented into a number of different pixel or colored subpixel electrodes. In such AMLCDs, each pixel or colored subpixel may be individually addressed via a corresponding conventional a-Si TFT or diode.

For example, electrode 21 may be divided into thirty separate and independent subpixel electrodes, ten of which are associated with corresponding blue filters (not shown) so as to define blue subpixels, another ten of which are associated with corresponding red filters (not shown) thereby defining red subpixels, and the remaining ten being associated with green color filters (not shown) so as to define green subpixels. The color filters (not shown) are disposed on the opposing side of LC layer 9 with respect to the segmented electrodes. In such an arrangement, the thirty subpixels may make up ten pixels, each pixel having a red, green, and blue subpixel therein arranged in a triangular fashion in certain embodiments.

With reference to FIGS. 4–6, in a typical operation of this first embodiment, the display operates as follows. White light is first emitted from conventional collimating backlight

3 and directed toward the rear side of the display panel. The light from backlight 3 hits rear polarizer 5 and is linearly polarized in accordance with polarization axes P_R. After being initially polarized, the linearly polarized light proceeds through rear transparent substrate 17, rear electrode(s) 21, and rear buffing or orientation film 7 before reaching liquid crystal layer 9.

When liquid crystal layer 9 is in the off-state, the light proceeding therethrough is twisted (preferably about In certain 90°) before exiting layer 9 and reaching front buffing film 11. However, when LC layer 9 has a voltage (e.g. about 6 volts) above V_{th} applied thereto and is therefore in the on-state, the polarization direction of the light reaching its rear surface remains substantially unchanged as it proceeds through layer 9 and exits its front surface adjacent front orientation film 11 because the application of voltage across layer 9 causes the LC molecules thereof to become substantially aligned vertically or "stand up" as known in the art. Accordingly, the polarization direction of the light exiting LC layer 9 depends upon the voltage applied across the liquid crystal material—the higher the voltage, the more the LC molecules become aligned and the less twisting which occurs.

After exiting the front or exit side of liquid crystal layer 9, the light proceeds through front orientation film 11, front transparent ITO electrode 23, subpixel color filters (not shown) if present, and front transparent substrate 19 before reaching uniaxial retardation film 13. As the light proceeds through retardation film 13, the film conventionally introduces a phase delay that substantially restores the original polarization state of the light to what it was before it entered liquid crystal layer 9 (assuming the display is in the "on-state").

A need for retardation film 13 arises because when a driving voltage is applied across LC layer 9, the liquid crystal molecules become aligned vertically, but never completely. In other words, the liquid crystal molecules, even when a high driving voltage is applied thereto, are tilted slightly from the vertical. This inevitable tilting of the LC molecules creates the need for retardation film 13 which in effect produces a phase delay which reverses the effect caused by the non-perfect vertical alignment of the LC molecules.

After exiting retardation film 13, the light which originated from backlight 3 reaches the interior side of front linear polarizer 15. As discussed above, the polarization direction of the light reaching front polarizer 15 depends upon the driving voltage (or absence thereof) applied across liquid crystal layer 9. Thus, with respect to LC pixels of the matrix array in the off-state, the polarization direction of light reaching front polarizer 15 is substantially aligned with transmission axis P_F which results in these off-state pixels appearing white or colored to the viewer.

However, with respect to on-state pixels in which a driving voltage $>V_{th}$ is applied across LC material 9, the polarization direction of light reaching front polarizer 15 is not substantially aligned with transmission axis P_F thus resulting in on-state pixels appearing darkened to viewer 1 because polarizer 15 substantially blocks the light from reaching viewer 1. In such a manner, the application of predetermined driving voltages to selective pixels or colored subpixels results in desired images being displayed to viewer 1.

FIG. 7 is an exploded schematic view of the optical components and their respective orientations of an LCD according to a second embodiment of this invention. This

second embodiment depicted in FIG. 7 differs from the first embodiment (FIGS. 4–6) in that the first embodiment is "X-buffed" and this second embodiment is "P-buffed". In other words, transmission axis P_R of rear linear polarizer 5 in this embodiment is substantially parallel to buffing direction B_R of rear orientation film 7, and transmission axis P_F of front polarizer 15 is substantially parallel to buffing direction B_F of front orientation film 11, thus defining a "P-buffed" display.

As will be appreciated by those of skill in the art, the display of the first embodiment may be adjusted so as to be transformed into the LCD of the second embodiment simply by rotating rear and front polarizers 5 and 15 respectively about 90° each, the rest of the cell such as LC layer 9, orientation films 7 and 11, retardation film 13, substrates 17 and 19, and electrodes 21 and 23 remaining substantially the same in both the first and second embodiments.

FIG. 8 is an exploded schematic view of the optical components and their respective orientations of an "X-buffed" LCD according to a third embodiment of this invention. While both the first and third embodiments illustrated and described herein are "X-buffed", the principal difference therebetween is the position of retardation film 13. As shown in FIG. 8, retardation film 13 is disposed rearward or on the backlight side of liquid crystal layer 9 as opposed to its disposition on the front side thereof in the first embodiment of this invention.

A significant advantage associated with the positioning of retardation film 13 rearward of liquid crystal layer 9 is the reduction of ambient light reflection off of the front of the display panel, this reduction being attributed to fewer mismatching indices of refraction forward of liquid crystal layer 9 as discussed in aforesaid Ser. No. 08/235,691.

With respect to the third embodiment shown in FIG. 8, optical axis R of retardation film 13 may be rotated clockwise or counterclockwise relative to direction R_0 and buffing direction B_F, counterclockwise rotation causing the viewing envelope to shift into the upper or positive vertical region as in the first embodiment and clockwise rotation causing the envelope to shift into the negative or lower vertical viewing region. Therefore, if film 13 is disposed on the viewer side of liquid crystal layer 9, it must be rotated clockwise in order to shift the viewing envelope into the upper or positive vertical region, while if retardation film 13 is disposed rearward of liquid crystal layer 9 as in FIG. 8, counterclockwise rotation of optical axis R relative to directions R_0 and B_F as shown in FIG. 8 will cause the viewing envelope to shift into the upper vertical region.

With respect to the optical components of the third embodiment, transmission axis P_R of rear polarizer 5 is substantially parallel to direction R_0 and buffing direction B_F. Likewise, transmission axis P_F of front polarizer 15 is substantially parallel to buffing direction B_R of rear orientation film 7, buffing directions B_F and B_R being substantially perpendicular to one another. With respect to the retardation value of retarder 13, each of the first, second, and third embodiments utilize the aforediscussed retardation values.

This invention will now be described with respect to certain examples as follows:

EXAMPLE 1

In this first Example, three separate normally white a-Si TFT driven twisted nematic AMLCDs were manufactured and tested for purposes of comparison. The three AMLCDs are referred to in this Example as Display "A", Display "B",

and Display "C" respectively. Each of the three AMLCDs of this Example utilized the same liquid crystal layer, RGB color filters, orientation films, electrodes, and transparent substrates. In other words, Displays "B" and "C" were constructed simply by adjusting or replacing the polarizers and/or retardation film 13.

The liquid crystal material of each display had a birefringence (ΔN) of about 0.084 at room temperature and was obtained from E. Merck Ltd. or its United States representative E.M. Industries, Inc., Hawthorne, N.Y. as Model No. ZLI-4718. Each of the three displays was tested at about 35°–45° C. The electrodes were conventional in nature and made of transparent ITO, the substrates were made of glass, and the buffing or orientation films were conventional in nature and made of a polyimide material. All three NW AMLCDs of this Example were of the RGB colored type and had red cell gaps "d" of about 5.6 μm, and green and blue cell gaps of about 5.3 μm, each pixel having a triad arrangement of RGB subpixels. White light emitted from conventional backlight 3 was utilized in all Examples herein.

The optical construction of Display "A" of this first Example is shown in FIGS. 4–6. NW Display "A" included from the rear forward toward viewer 1, conventional backlight 3, conventional linear polarizer 5 with transmission axis P_R, rear transparent glass substrate 17, rear segmented pixel and RGB subpixel electrodes 21, rear orientation film 7 having buffing direction B_R, liquid crystal layer 9, front orientation film 11 having buffing direction B_F, front electrode 23, RGB color filters (not shown) corresponding to each subpixel segment of electrode 21, front transparent glass substrate 19, uniaxial positively birefringent retardation film 13 having optical axis R, and finally front linear polarizer 15 having transmission axis P_F.

With respect to Display "A", transmission axis P_R of rear polarizer 5 was substantially parallel to buffing direction B_F of front orientation film 11. Also, transmission axis P_F of front polarizer 15 was substantially parallel to rear buffing direction B_R of orientation film 7 thus defining an "X-buffed" AMLCD, buffing directions B_F and B_R being substantially perpendicular to one another.

Retardation film 13 was positively birefringent and had a retardation value of 140 nm. Optical axis R of retardation film 13 was rotated about 8.5° in the clockwise direction relative to axis P_F and direction B_R so as to define Θ as shown in FIGS. 4–5 as about 8.5°. Retardation film 13 of Display "A" was obtained from Nitto Corporation, Japan, or Nitto Denko America, New Brunswick, N.J., as Model No. NRF140.

Rear and front linear polarizers 5 and 15 of all Examples herein were conventional in nature and obtained from Nitto Denko America, Model No. G 1220DUN.

FIG. 9 is a contrast ratio contour plot of Display "A" of this Example when a driving voltage of about 6.8 volts was applied thereto and white light was emitted from backlight 3. As shown, the high contrast viewing zone was shifted vertically into the positive vertical region (above the 0° vertical viewing axis) by the aforesaid clockwise rotation of optical axis R of retardation film 13. This display had at least about a 10:1 contrast ratio at +10° vertical over a total range of about 110° horizontal, this being an improvement of about 40° with respect to the light valve of prior art FIG. 1 at the same 10° vertical viewing axis. In a similar manner, Display "A" had at least about a 10:1 contrast ratio at +50° vertical that extended over a total of about 95° horizontal, this 95° horizontal range being a signficant improvement over the contrast ratio at 50° vertical with respect to the light valve of FIG. 1.

As shown, the viewing zone or envelope of Display "A" when about 6.8 volts was applied thereto was fairly uniform (or unskewed) in nature. Additionally, high contrast ratios (e.g. 50:1) of Display "A" extended over significantly greater horizontal and vertical expanses than did their corresponding ratios in the light valve of prior art FIG. 1. For Example, the 50:1 contrast ratio of Display "A" at +10° vertical extended over a total of about 80° horizontal as shown in FIG. 9, while the corresponding 50:1 contrast ratio curve in prior art FIG. 1 at 10° vertical extended only over about 40° horizontal. Thus, it is evident that the addition of retardation film 13 with its corresponding retardation value and optical orientation resulted in a significant improvement with respect to contrast ratio.

FIG. 10 is a contrast ratio contour plot of Display "A" of this Example when about a 6.0 volt driving voltage was applied thereto. As shown, the slight reduction in driving voltage resulted in the contrast ratio contours slightly shrinking horizontally in the extreme upper vertical viewing region (e.g. 60° vertical).

FIG. 11 is an intensity (fL) vs driving voltage plot of Display "A". As shown, Display "A" had significantly reduced inversion with respect to that of the prior art light valve shown in FIG. 2. This is evident by the substantial elimination of the prior art inversion humps present at about 3.0 volts and greater. No such inversion humps are shown in FIG. 11 thus illustrating the significant improvement over the prior art with respect to inversion at the illustrated horizontal viewing angles along the 0° vertical viewing axis. The elimination of the inversion humps of the prior art allows Display "A" to be easily and effectively driven with a plurality of gray level driving voltages while allowing viewers at different viewing angles to see substantially the same image with respect to color and other important viewing characteristics.

FIG. 12(*a*) is a contrast ratio contour plot of NW a-Si TFT driven "X-buffed" Display "B" of this Example, Display "B" being manufactured and tested for purposes of comparison with Display "A". As stated above, Display "B" was manufactured utilizing the same liquid crystal material, electrodes, RGB color filters, orientation films, TFTs, and transparent substrates as Display "A". The only difference between Display "A" and Display "B" was that the retardation value of uniaxial positively birefringent retardation film 13 of Display "B" was about 350 nm instead of the 140 nm value of Display "A" and optical axis R of retardation film 13 was substantially parallel to directions R_0 and B_R. Thus, by comparing the results of displays "A" and "B", one may easily see the improvement resulting from the use of a retardation value in the range of about 100–200 nm (e.g. 140 nm) as opposed to retardation values greater than about 300 nm.

As shown in FIG. 12(*a*) the high contrast viewing envelope of the 350 nm retardation film Display "B" was significantly smaller with respect to contrast ratio than was that of Display "A" shown in FIG. 9. By comparing FIGS. 9 and 12(*a*), it is clear that use of the higher value retardation film resulted in a smaller viewing envelope both vertically and horizontally.

Further evident from comparing FIGS. 9 and 12(*a*) is the fact that Display "A" had higher contrast ratios (e.g. 50:1 and greater) over a larger range of viewing angles than did Display "B" thus resulting in improved viewing characteristics. Thus, this additional advantage associated with the lower value retardation film is clear.

FIG. 12(*b*) is a contrast ratio contour plot of NW a-Si TFT driven Display "C" of this Example. Display "C" differed from Display "A" in that Display "C" was "P-buffed" as shown in FIG. 7 (instead of "X-buffed") and utilized a uniaxial positively birefringent retardation film 13 having a retardation value of about 350 nm. Furthermore, optical axis R of retardation film 13 in Display "C" was substantially parallel to axis P_R and direction B_R (θ=about 0°).

All three NW AMLCDs of this Example had their respective retardation films disposed on the forward or viewer side of liquid crystal material 9 and sandwiched between front substrate 19 and front polarizer 15.

Display "C", which is similar to NW displays described in U.S. Pat. No. 5,184,236, had its contrast ratio contour plot illustrated when about 6.0 volts was applied thereto in FIG. 12(*b*). As shown in FIG. 12(*b*) as compared to FIG. 9, Display "C" had significantly lower contrast ratio expanses both vertically and horizontally than did Display "A". Additionally, the extent of higher contrast ratios (e.g. 50:1) in Display "A" was greater than that of Display "C" as is evident by comparing FIG. 9 with FIG. 12(*b*).

The orientations of retardation film optical axis R in Displays "A", "B", and "C", of course, resulted in the viewing envelopes of Displays "B" and "C" not being shifted vertically as was the envelope of Display "A".

EXAMPLE 2

A "P-buffed" normally white twisted nematic light valve was manufactured and tested at about 35°–40° C. in this Example. This light valve had optical orientations similar to those shown in FIG. 7 and included from the rear forward toward viewer 1 conventional backlight 3, rear linear polarizer 5 with transmission axis P_R, rear transparent glass substrate 17, rear continuous electrode 21, rear orientation film 7 with buffing direction B_R, liquid crystal layer 9 having a thickness or cell gap "d" of about 5.86 μm, front orientation film 11 with buffing direction B_F, front continuous electrode 23, front transparent glass substrate 19, uniaxial positively birefringent retardation film 13 having a retardation value of about 120 nm, and finally front linear polarizer 15 having transmission axis P_F.

Retardation film 13 had its optical axis R rotated clockwise about 20° relative to directions R_0 and B_R so as to shift the viewing envelope into the positive vertical viewing region. In other words, Θ equaled about 20° as shown in FIG. 7.

Retardation film 13 of this Example was positively birefringent, uniaxial, and was obtained from Nitto Denko America, New Brunswick, N.J., Model No. NRF120. The liquid crystal material was identical to the type utilized in the displays of Example 1, as were the polyimide orientation films, glass substrates, and polarizers. Because this Example utilized a light valve, both electrodes 21 and 23 were continuous in nature as opposed to the segmented design of the rear electrode of each AMLCD in Example 1.

FIG. 13 is a contrast ratio contour plot of the NW light valve of Example 2 when about a 5.0 volt driving voltage was applied thereto. As shown, the 20° clockwise rotation of optical axis R of retardation film 13 resulted in the shifting of the viewing zone or envelope into the positive vertical region as is evident by FIG. 13. Furthermore, the use of the 120 nm retardation film resulted in high contrast ratios over a wide range of horizontal and vertical viewing angles as shown. Thus, the advantages of such a retardation value and the 20° rotation of optical axis R are self-evident in view of the superior viewing characteristics exhibited.

FIG. 14 is a contrast ratio contour plot of the NW light valve of this Example when about a 4.0 volt driving voltage was applied. As shown, the viewing zone remained in the upper or positive vertical region and was substantially uniform and unskewed in nature.

An advantage of particular interest associated with the light valve of this Example is its good contrast at driving voltages of about 4–5 volts. Certain driver chips often do not allow displays to be driven above 6 volts. In other words, such chips provide for maximum driving voltages of only about 6 volts, this meaning that many of the gray level driving voltages are around 4–6 volts. Therefore, the superior contrast behavior of this light valve at such driving voltages is a distinct advantage. The better behavior of this light valve at lower driving voltages is clearly an improvement over the prior art.

EXAMPLE 3

A normally white a-Si TFT driven twisted nematic AMLCD of the P-buffed type was manufactured and tested at about 35°–40° C. in this Example. The liquid crystal material was the same as discussed above in Examples 1 and 2, with this AMLCD having a cell gap "d" of about 5.3 μm in each of the red, green, and blue subpixels. Each pixel of this AMLCD included an RGB triad of subpixels. Unlike the other Examples herein, this AMLCD was driven with a conventional Gross Tester in that all column and row address lines were driven together.

As shown generally in FIG. 7, the AMLCD of Example 3 included from the rear forward conventional backlight 3, conventional polarizer 5 having transmission axis P_R, transparent rear glass substrate 17, transparent ITO segmented subpixel or pixel electrodes 21, rear orientation film 7 having buffing direction B_R, liquid crystal layer 9 having a RGB cell gap of about 5.3 μm, front orientation film 11 with buffing direction B_F, front continuous electrode 23, red, green, and blue color filters (not shown) corresponding to each subpixel electrode segment, front transparent glass substrate 19, uniaxial positively birefringent retardation film 13 having a retardation value of about 140 nm, and finally front linear polarizer 15 having transmission axis P_F.

Retardation film 13 was again obtained from Nitto Denko America, New Brunswick, N.J., as Model No. NRF140 and was oriented such that its optical axis R was rotated clockwise about 5° relative to direction B_R and axis P_R. In other words, Θ as shown in FIG. 7 was about 5°.

As shown in FIG. 15, the AMLCD of this Example had its viewing zone or envelope shifted into the positive vertical region by the 5° rotation of retardation film axis R, the viewing envelope being substantially uniform in nature as shown.

This concludes the Examples herein.

As is evident from the results of the aforesaid Examples, the provision of a retardation film having a retardation value of from about 100–200 nm (or 100–250 nm) on a single side of the liquid crystal layer significantly improves the viewing characteristics of a display with respect to both constrast ratio and inversion. As will be appreciated by those of skill in the art, the provision of a normally white twisted nematic LCD having an enlarged and vertically shiftable viewing zone with reduced inversion is a significant improvement over conventional normally white LCDs, this improvement allowing the substantially cheaper to manufacture NW displays to take the place of more expensive normally black displays.

Furthermore, the ability to shift the viewing zone vertically into either the positive or negative vertical viewing

region allows the manufacturer to custom make or tailor each AMLCD according to the needs of specific customers. For Example, one customer may require an AMLCD to be mounted in the lower portion of an avionic cockpit such that the pilot is forever looking downward at the display thus requiring the AMLCD to have high contrast ratios and reduced inversion in the upper or positive vertical region. In such a case, the desired viewing characteristics may be achieved simply by rotation of retardation film 13 as discussed above. Thus, the designs of the different embodiments of this invention allow different specifications to be realized.

FIG. 16 illustrates another embodiment of this invention where first and second biaxial (or uniaxial) retarders are located on the rear side of the liquid crystal layer. Such an embodiment is further described and illustrated in U.S. Pat. No. 5,594,568, incorporated herein by reference above. Alternatively, the two biaxial retarders may be located on opposite sides of the liquid crystal layer as described and illustrated in U.S. Pat. No. 5,570,214, also incorporated herein by reference above.

The pre-tilt angle of the displays and light valves herein may be about 3° in certain embodiments, and the value of "d/p" (thickness/natural pitch of the liquid crystal material) of the liquid crystal layers may be set to about 0.25.

Once given the above disclosure, many other features, modifications, and improvements will become apparent to the skilled artisan. Such other features, modifications, and improvements are, therefore, considered to be a part of this invention, the scope of which is to be determined by the following claims:

We claim:

1. A normally white liquid crystal display capable of displaying an image to a viewer, the display comprising:

a pair of electrodes sandwiching a twisted nematic liquid crystal layer therebetween, said pair of electrodes for applying a voltage across said liquid crystal layer;

first and second orientation layers disposed adjacent said liquid crystal layer on opposite sides thereof, said first and second orientation layers for aligning liquid crystal molecules of said liquid crystal layer in a predetermined manner;

first and second biaxial retardation members provided in the display;

said liquid crystal layer being provided so as to twist at least one wavelength of light passing therethrough from about 80°–100°;

each of said first and second biaxial retardation members at at least one location therein being defined by $n_x>n_y>n_z$, wherein n_x, n_y, and n_z are indices of refraction with the "z" direction being perpendicular to the "x" and "y" directions; and

wherein for each of said first and second biaxial retardation members $d \cdot \Delta n_{zx}$ is from about −100 to −200 nm, and wherein said first and second biaxial retardation members are oriented with respect to each other so that the display can achieve a white light contrast ratio of at least about 30:1 over a horizontal viewing angular span of at least about 80° and over a vertical viewing angular span of greater than about 30°.

2. A normally white liquid crystal display comprising:

a rear, light entrance polarizer having a transmission axis oriented in a first direction;

a front, light exit polarizer having a transmission axis oriented in a second direction wherein said first and second directions are oriented so as to define a normally white display;

first and second negative biaxial retarders, wherein each of said first and second negative biaxial retarders has a retardation value $d \cdot \Delta n_{zy}$ of from about −10 to −100 nm where "d" is the thickness of the retarder and at least a portion of the retarder has indices of refraction n_x, n_y, and n_z where n_x and n_y define a plane and n_z is oriented in a direction perpendicular to said plane; and

wherein said retarders are so arranged with respect to one another so as to achieve a white light contrast ratio of at least about 10:1 over a horizontal viewing angular span, at a predetermined vertical viewing angle, of at least about 120°, and over a vertical viewing angular span of greater than about 60° at a predetermined horizontal viewing angle.

3. The normally white display of claim 2, further including a liquid crystal layer having a Δn value of from about 0.075 to 0.095, and wherein the first and second negative biaxial retarders are located on the same side of the liquid crystal layer.

4. A normally white liquid crystal display for displaying an image to a viewer, the liquid crystal display comprising:

a liquid crystal layer disposed between first and second electrodes, said first and second electrodes for applying a voltage across said liquid crystal layer;

said liquid crystal layer being disposed between first and second polarizers oriented in a manner such that the display is of a normally white type;

first and second negatively birefringent retardation systems located on opposite sides of said liquid crystal layer so that said liquid crystal layer is disposed between said first and second negatively birefringent retardation systems, each of said first and second negatively birefringent retardation systems having a retardation value of $d \cdot \Delta_{zy}$ from about −10 to −100 nm, where the retardation value is defined by a thickness of the negatively birefringent retardation system multiplied by a difference between two of three indices of refraction; and

wherein said first and second negatively birefringent retardation systems are so arranged with respect to one another so that the display can achieve a white light contrast ratio of at least about 10:1 over a horizontal viewing angular span of at least about 120° at a vertical viewing angle, and over a vertical viewing angular span of greater than about 60° at a horizontal viewing angle.

5. The display of claim 4, wherein each of said first and second negatively birefringent retardation systems includes a retarder having three unequal indices of refraction.

6. The display of claim 4, wherein each of said first and second negatively birefringent retardation systems includes a negatively birefringent biaxial retardation film.

7. The display of claim 4, wherein said display is capable of outputting a contrast ratio at least about 30:1 at viewing angles at about +15° vertical over a horizontal range of at least about 75°.

8. The display of claim 7, wherein the display is capable of outputting a contrast ratio of at least about 50:1 over a horizontal viewing angular span of at least about 80°.

* * * * *

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The JS-44 civil cover sheet and the information contained herein neither replace nor supplement the filing and service of pleadings or other papers as required by law, except as provided by local rules of court. This form, approved by the Judicial Conference of the United States in September 1974, is required for the use of the Clerk of Court for the purpose of initiating the civil docket sheet. (SEE INSTRUCTIONS ON THE REVERSE OF THE FORM.)

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Guardian Industries Corp.

(b) COUNTY OF RESIDENCE OF FIRST LISTED PLAINTIFF ______
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DEFENDANTS

Innolux Display Corp.

COUNTY OF RESIDENCE OF FIRST LISTED DEFENDANT ______
(IN U.S. PLAINTIFF CASES ONLY).

(c) ATTORNEYS (FIRM NAME, ADDRESS AND TELEPHONE NUMBER)
Richard K. Herrmann #405
Morris James
500 Delaware Avenue, Suite 1500
Wilmington, DE 19899-2306
302-888-6800

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☐ 365 Personal Injury – Product Liability
☐ 368 Asbestos Personal Injury Product Liability

PERSONAL PROPERTY
☐ 370 Other Fraud
☐ 371 Truth in Lending
☐ 380 Other Personal Property Damage
☐ 385 Property Damage Product Liability

FORFEITURE/PENALTY
☐ 610 Agriculture
☐ 620 Other Food & Drug
☐ 625 Drug Related Seizure of Property 21 USC 881
☐ 630 Liquor Laws
☐ 640 R. R. & Truck
☐ 650 Airline Regs.
☐ 660 Occupational Safety/Health
☐ 690 Other

LABOR
☐ 710 Fair Labor Standards Act
☐ 720 Labor/Mgmt Relations
☐ 730 Labor/Mgmt Reporting & Disclosure Act
☐ 740 Railway Labor Act
☐ 790 Other Labor Litigation
☐ 791 Empl. Ret. Inc Security Act

BANKRUPTCY
☐ 422 Appeal 28 USC 158
☐ 423 Withdrawal 28 USC 157

PROPERTY RIGHTS
☐ 820 Copyrights
☒ 830 Patent
☐ 840 Trademark

SOCIAL SECURITY
☐ 861 HIA (1395ff)
☐ 862 Black Lung (923)
☐ 863 DIWC/DIWW (405(g))
☐ 864 SSID Title XVI
☐ 865 RSI (405(g))

FEDERAL TAX SUITS
☐ 870 Taxes (U.S. Plaintiff or Defendant)
☐ 871 IRS – Third Party 26 USC 7609

OTHER STATUTES
☐ 400 State Reapportionment
☐ 410 Antitrust
☐ 430 Banks and Banking
☐ 450 Commerce/ICC Rates/etc.
☐ 460 Deportation
☐ 470 Racketeer Influenced and Corrupt Organizations
☐ 810 Selective Service
☐ 850 Securities/Commodities/ Exchange
☐ 875 Customer Challenge 12 USC 3410
☐ 891 Agricultural Arts
☐ 892 Economic Stabilization Act
☐ 893 Environmental Matters
☐ 894 Energy Allocation Act
☐ 895 Freedom of Information Act
☐ 900 Appeal of Fee Determination Under Equal Access to Justice
☐ 950 Constitutionality of State Statutes
☐ 890 Other Statutory Actions

REAL PROPERTY
☐ 210 Land Condemnation
☐ 220 Foreclosure
☐ 230 Rent Lease & Ejectment
☐ 240 Torts to Land
☐ 245 Tort Product Liability
☐ 290 All Other Real Property

CIVIL RIGHTS
☐ 441 Voting
☐ 442 Employment
☐ 443 Housing/ Accommodations
☐ 444 Welfare
☐ 440 Other Civil Rights

PRISONER PETITIONS
☐ 510 Motions to Vacate Sentence
HABEAS CORPUS:
☐ 530 General
☐ 535 Death Penalty
☐ 540 Mandamus & Other
☐ 550 Civil Rights
☐ 555 Prison Condition

VI. CAUSE OF ACTION (CITE THE U.S. CIVIL STATUTE UNDER WHICH YOU ARE FILING AND WRITE BRIEF STATEMENT OF CAUSE. DO NOT CITE JURISDICTIONAL STATUTES UNLESS DIVERSITY.)
Action for patent infringement under 35 U.S.C. §§ 1 et seq.

VII. REQUESTED IN COMPLAINT: ☐ CHECK IF THIS IS A **CLASS ACTION** UNDER F.R.C.P. 23
DEMAND $
CHECK YES only if demanded in complaint:
JURY DEMAND: ☒ YES ☐ NO

VIII. RELATED CASE(S) IF ANY (See instructions):
JUDGE
DOCKET NUMBER

DATE
December 8, 2006

SIGNATURE OF ATTORNEY OF RECORD

RKH

FOR OFFICE USE ONLY

RECEIPT# ______ AMOUNT ______ APPLYING IFP ______ JUDGE ______ MAG. JUDGE ______

AO FORM 85 RECEIPT (REV. 9/04)

United States District Court for the District of Delaware

Civil Action No. 06-748

ACKNOWLEDGMENT OF RECEIPT FOR AO FORM 85

NOTICE OF AVAILABILITY OF A UNITED STATES MAGISTRATE JUDGE TO EXERCISE JURISDICTION

I HEREBY ACKNOWLEDGE RECEIPT OF 1 COPIES OF AO FORM 85.

12-8-06
(Date forms issued)

Joseph J. Saienni III
(Signature of Party or their Representative)

Joseph J- Saienni III
(Printed name of Party or their Representative)

Note: Completed receipt will be filed in the Civil Action